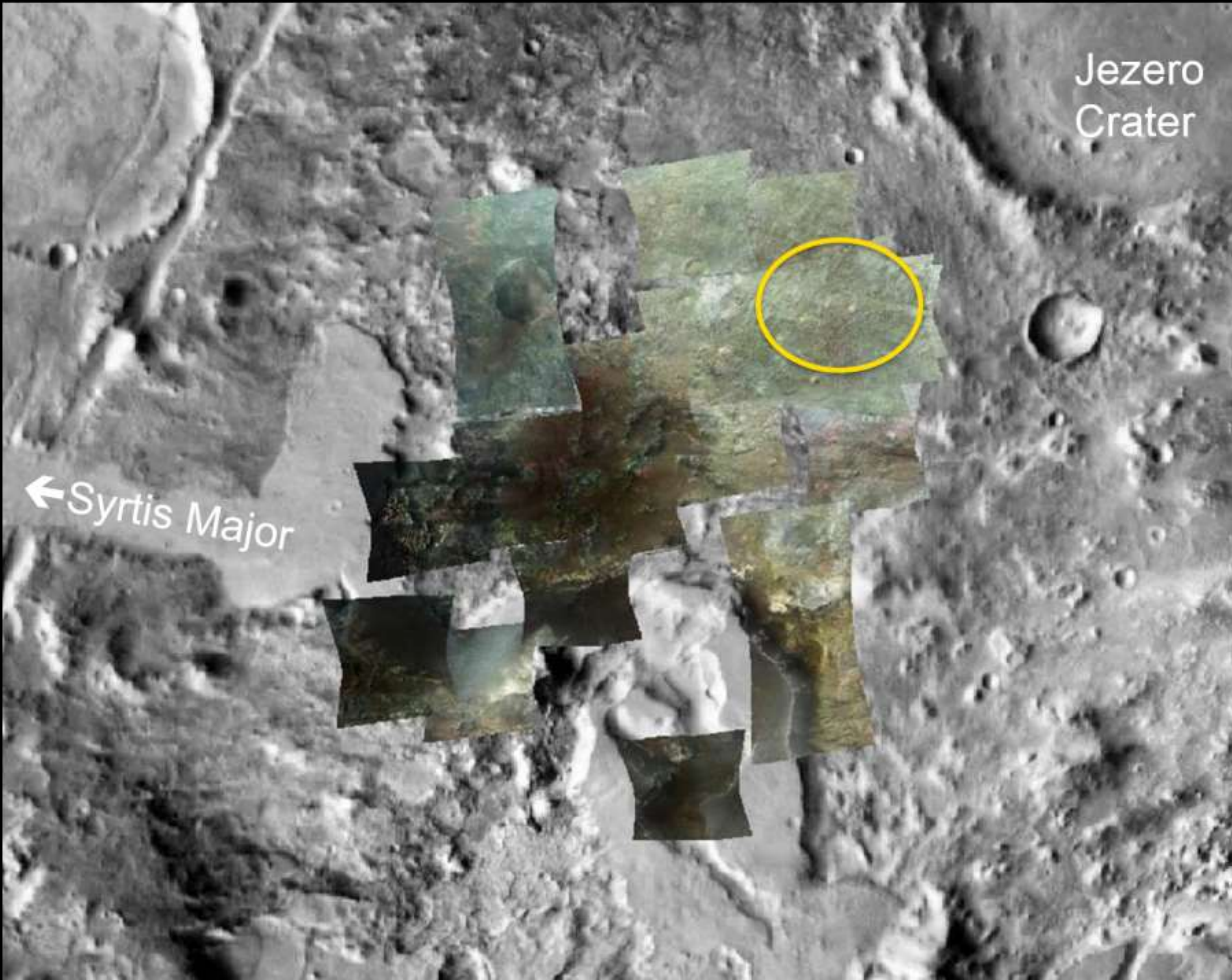
Multiple Habitable Environments across the Noachian-Hesperian Environmental Transition: Phyllosilicates, Carbonate, Sulfates, and Multiple Igneous Units in Stratigraphy at the Isidis-Syrtis Major Contact

Mustard, J., Ehlmann, B., Wiseman, S., Bramble, M., Cannon, K., Goudge, T., Viviano-Beck, C., Skok, J. R., Amador, E., Des Marais, D., Head, J., Salvatore, M., Milliken, R., and Quinn, D

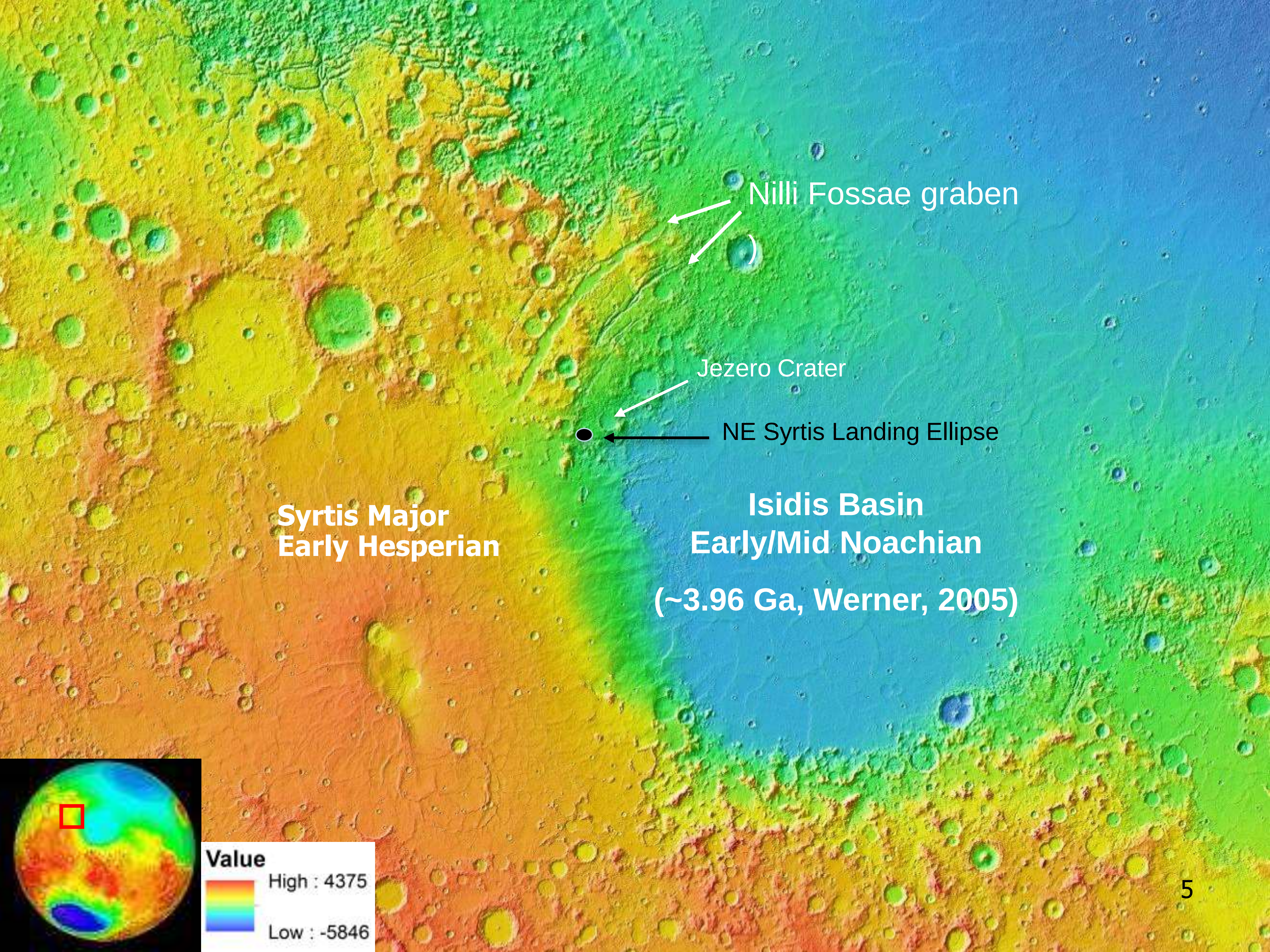

Jezero
Crater
Syrtis Major

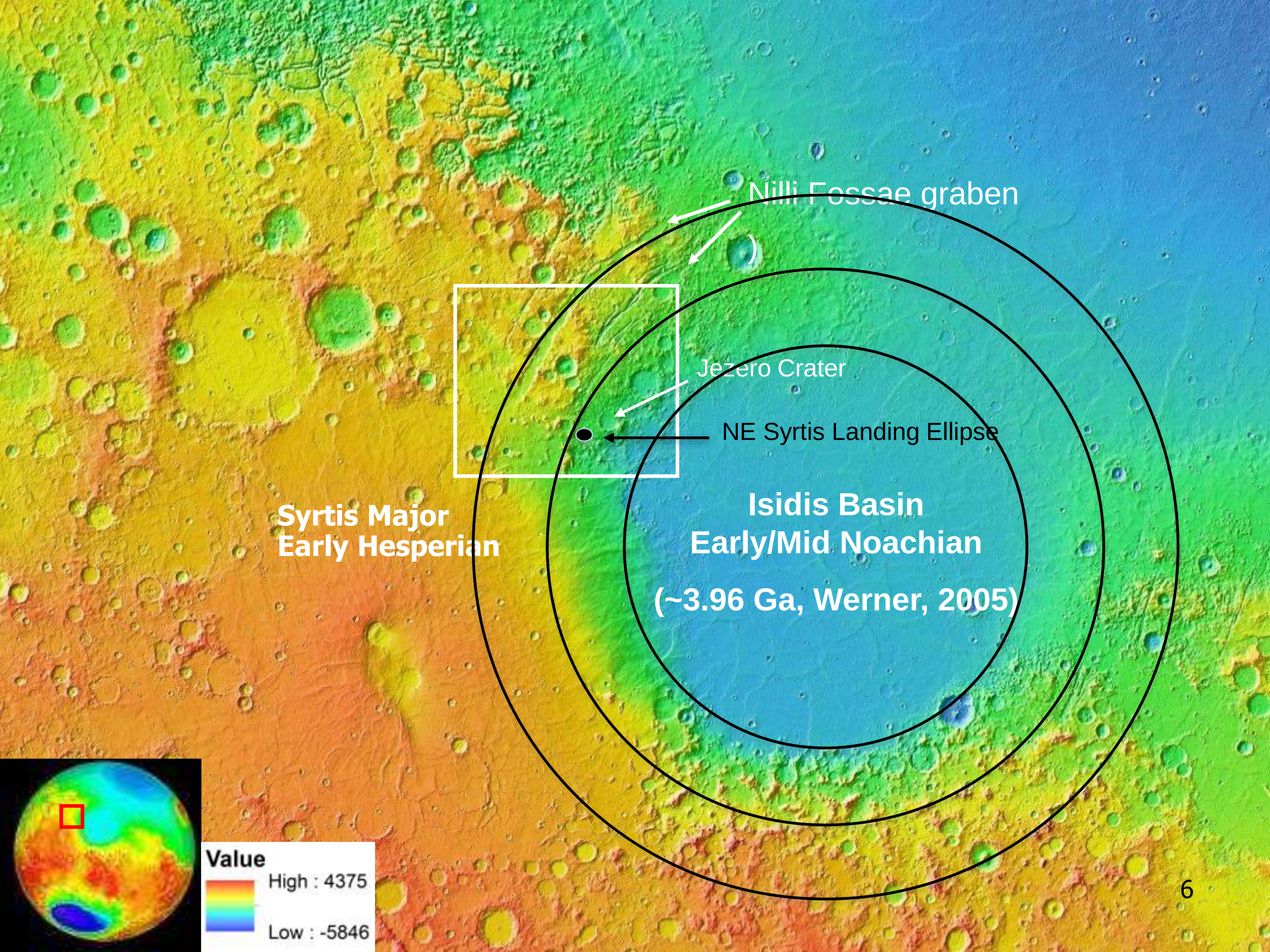
Compelling Mars and Astrobiology Land-on Science

- Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  - early crustal: creation or distribution by impact? Phyllosilicate formation
  - carbonate/serpentine: surface alteration or hydrothermal?
  - layered phyllosilicates (Al- over Fe/Mg)
  - sedimentary sulfate formation
- A record of aqueous low-T geochemistry preserved in-situ, in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting well-suited for the M2020 measurements and caching
- Key stratigraphies from Noachian and Hesperian eras
- Hydrothermal, pedogenic and sedimentary environments
- Multiple igneous units of distinct age

How NE Syrtis Meets Mars-2020 Site Selection Criteria

Obj. A	1. **Geologic setting and history of the landing site can be characterized and understood** w/ orbital and in-situ obs.		-clear timing constraints (EN to EH -multiple well-ordered strat. Units, delineated with orbital composition and morphology
Obj. B	2a. Landing site w/ **ancient habitable enviro.**		-carbonate formation by neutral alk waters (HT or weath.)+ Deep biosphere
	2b. **Rocks with high biosignature preservation potential** are available and **are accessible** to rover instr. astriobio. investigation.		"Phyllosilicate Deep Biosphere" "Sulfate Sediments" "Carbonate/Partially Serpentinized: Deep Biosphere"
Obj. C	3a. Offers **abundance, diversity, and quality of samples suitable for addressing key astrobio. questions if/when they are returned** to Earth.		-yes: Carbonate, mineralized fracture zones, sulfate deposits, phyllosilicate-bearing basement as window to deep biosphere
	3b. Offers **abundance, diversity, and quality of samples for addressing key planetary evolution questions** if/when they are returned to Earth.		-planetary formation and evolution, basin forming processes, hydration and crustal alteration, two dateable surfaces in extended mission, Noachian volcanism and putonism.


Nilli Fossae graben
Jezero Crater
NE Syrtis Landing Ellipse
Syrtis Major
Early Hesperian
Isidis Basin
Early/Mid Noachian
(~3.96 Ga, Werner, 2005)
Value
High : 4375
Low : -5846



Nilli Fossae graben
)
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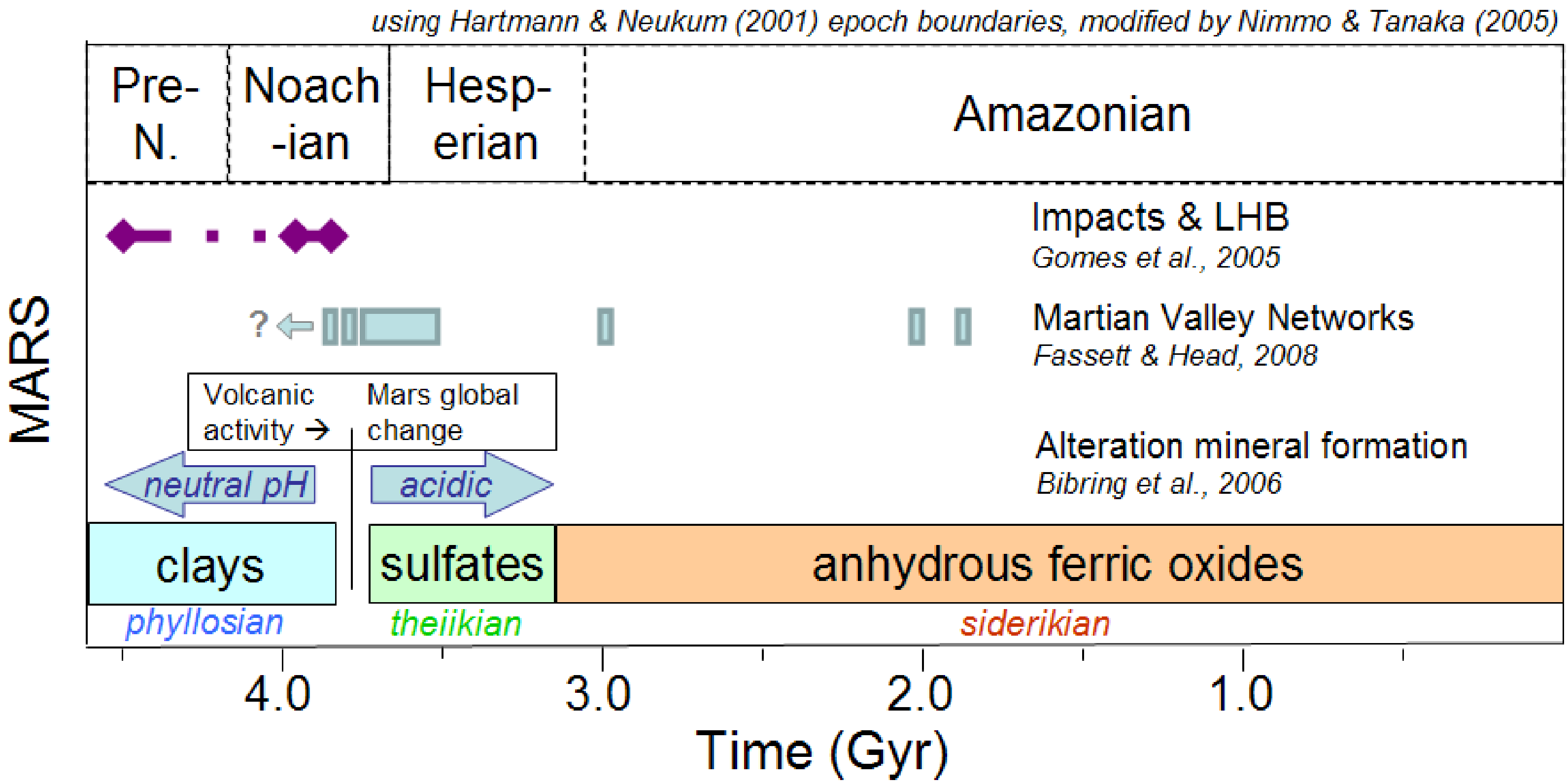
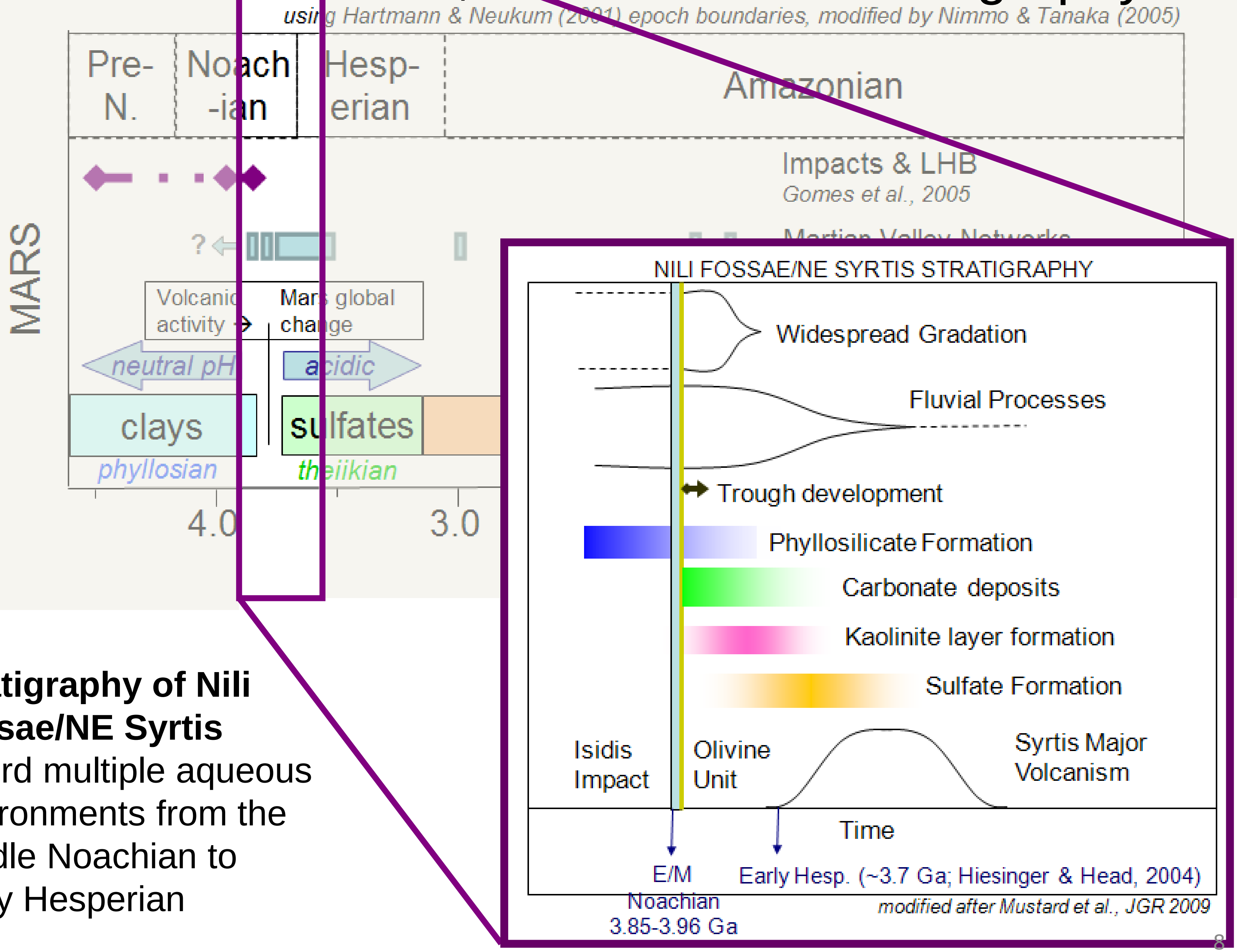
Well Understood, Time-Ordered Stratigraphy



Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian

Well Understood, Time-Ordered Stratigraphy



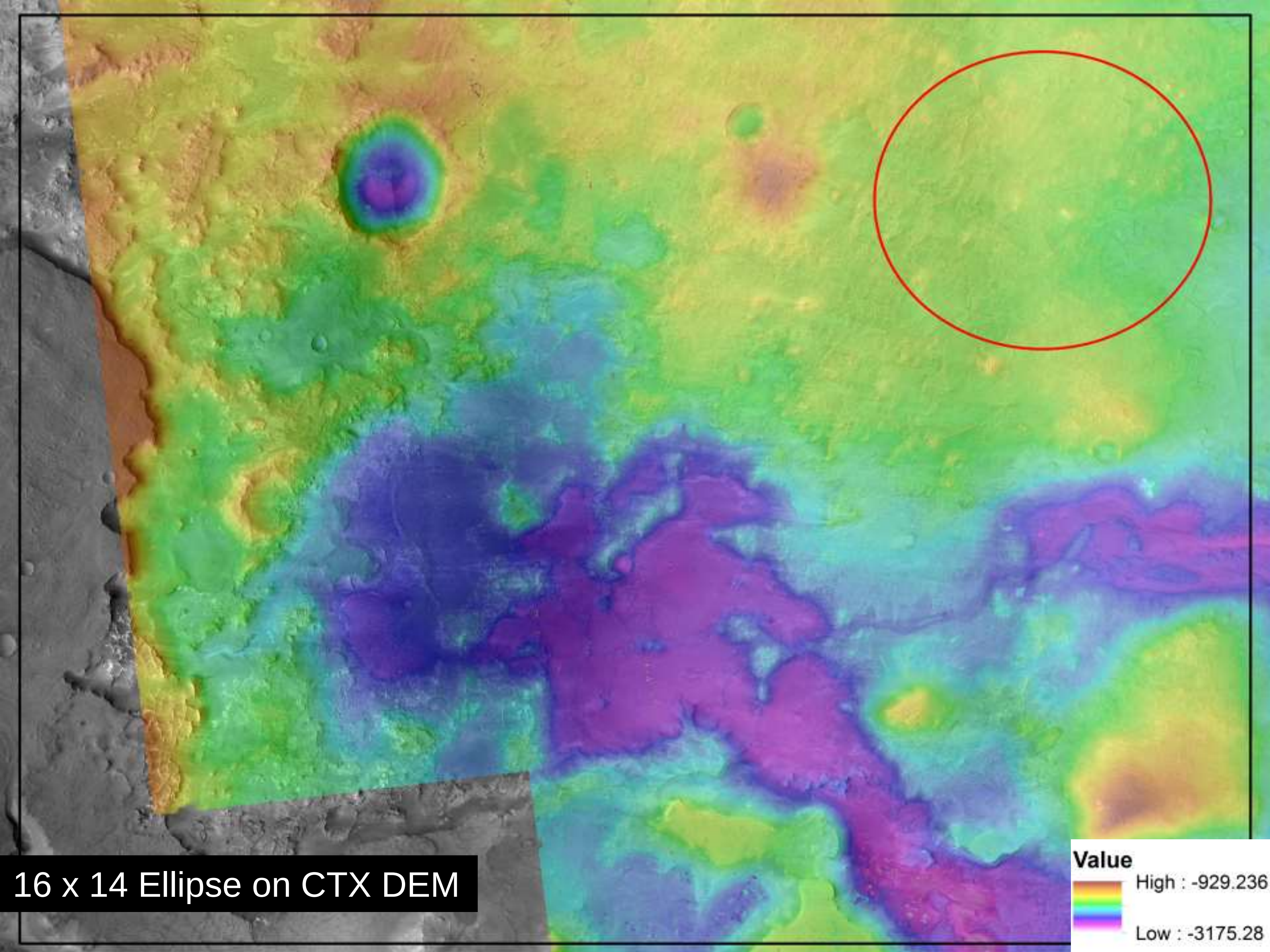
Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian

Major Hypotheses to be Tested

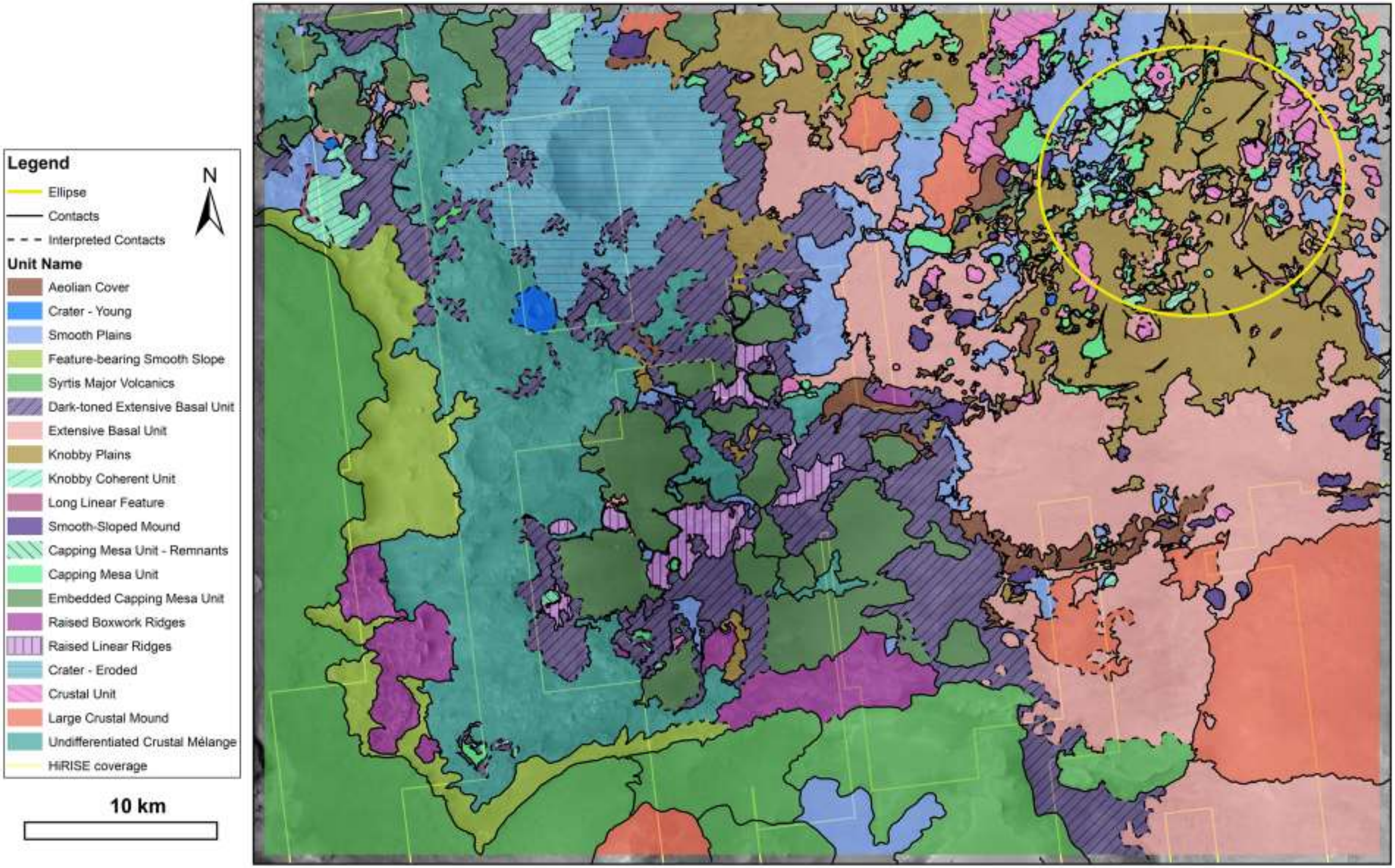
Olivine-bearing regional unit	• Ultramafic **volcanic** emplaced post-Isidis • Ultramafic **impact melt** from Isidis that tapped the mantle
Olivine-Magnesite Mineral Assemblage	• Near-surface weathering • **Serpentinizing hydrothermal systems** • Aqueous alteration in a metamorphic setting • Sedimentary/lacustrine deposits within ultramafic catchments

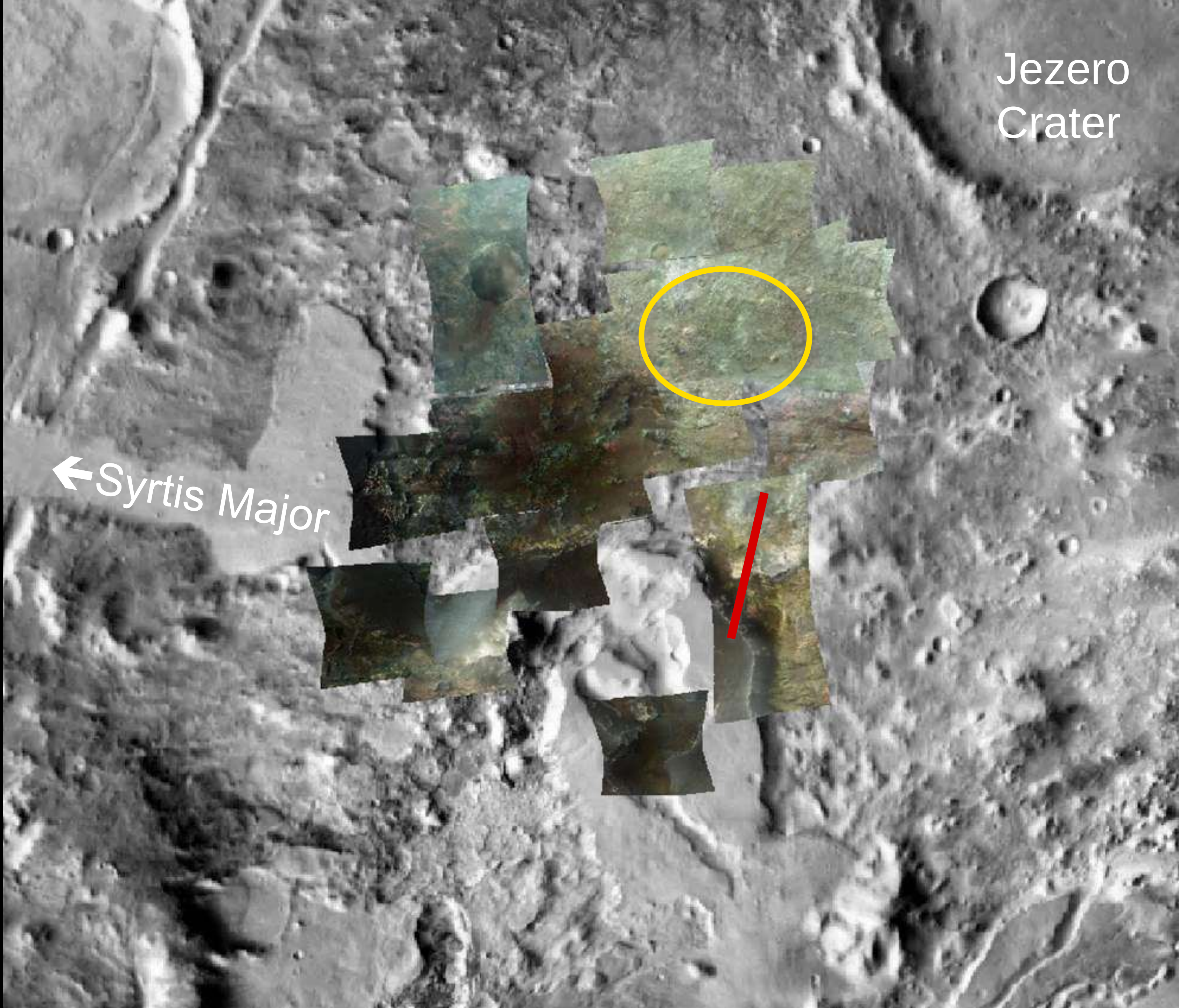
Megabreccia with phyllosilicate and unaltered igneous outcrops	• Altered with phyllosilicate: Low-T subsurface vs buried sediments
	• Unaltered (igneous)
	  • Remnants of Mars primary crust
	  • Noachian-aged low-Ca pyroxene lavas

Layered kaolinite-bearing capping stratigraphy:	• Extensive leaching during a period of vertically integrated water cycle • Acid leaching and snow melt
Erosionally resistant ridges	• Fracture zones mineralized with **hydrothermal precipitates** • Breccia Dikes
Hesperian-aged Sulfate stratigraphy	• Sedimentary deposition • Alteration of basalt and Box-work structures with jarosite: • Exiting vs. infiltrating acid waters
Syrtis Major Hesperian volcanics	• **Calibration of crater chronology**, testing the formation mechanism (chemistry and mineralogy), validating remote sensing


16 x 14 Ellipse on CTX DEM
Value
High : -929.236
Low : -3175.28

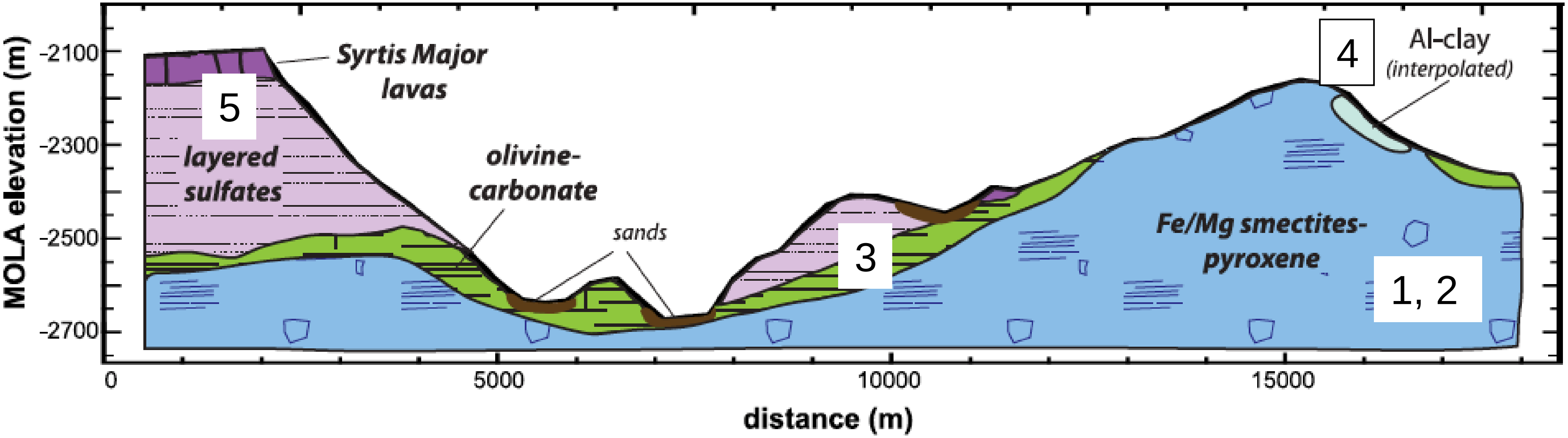
Mapping Northeast Syrtis Major




Jezero
Crater
Syrtis Major

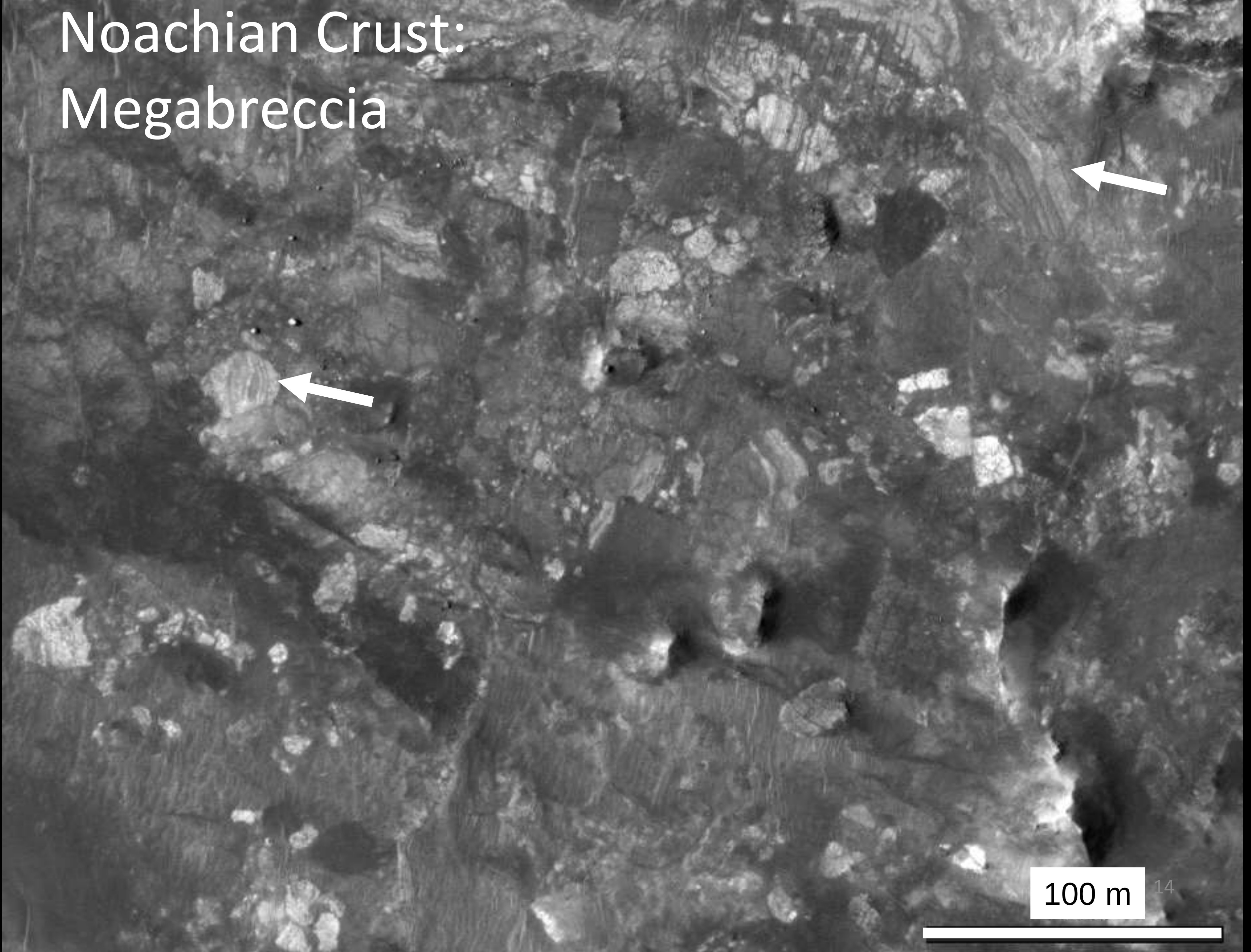
Regional Stratigraphy provides the context for in-ellipse and go-to science

Morphgeologic mapping establishes the local stratigraphy tied to the regional stratigraphy



Ehlmann and Mustard GRL 2013

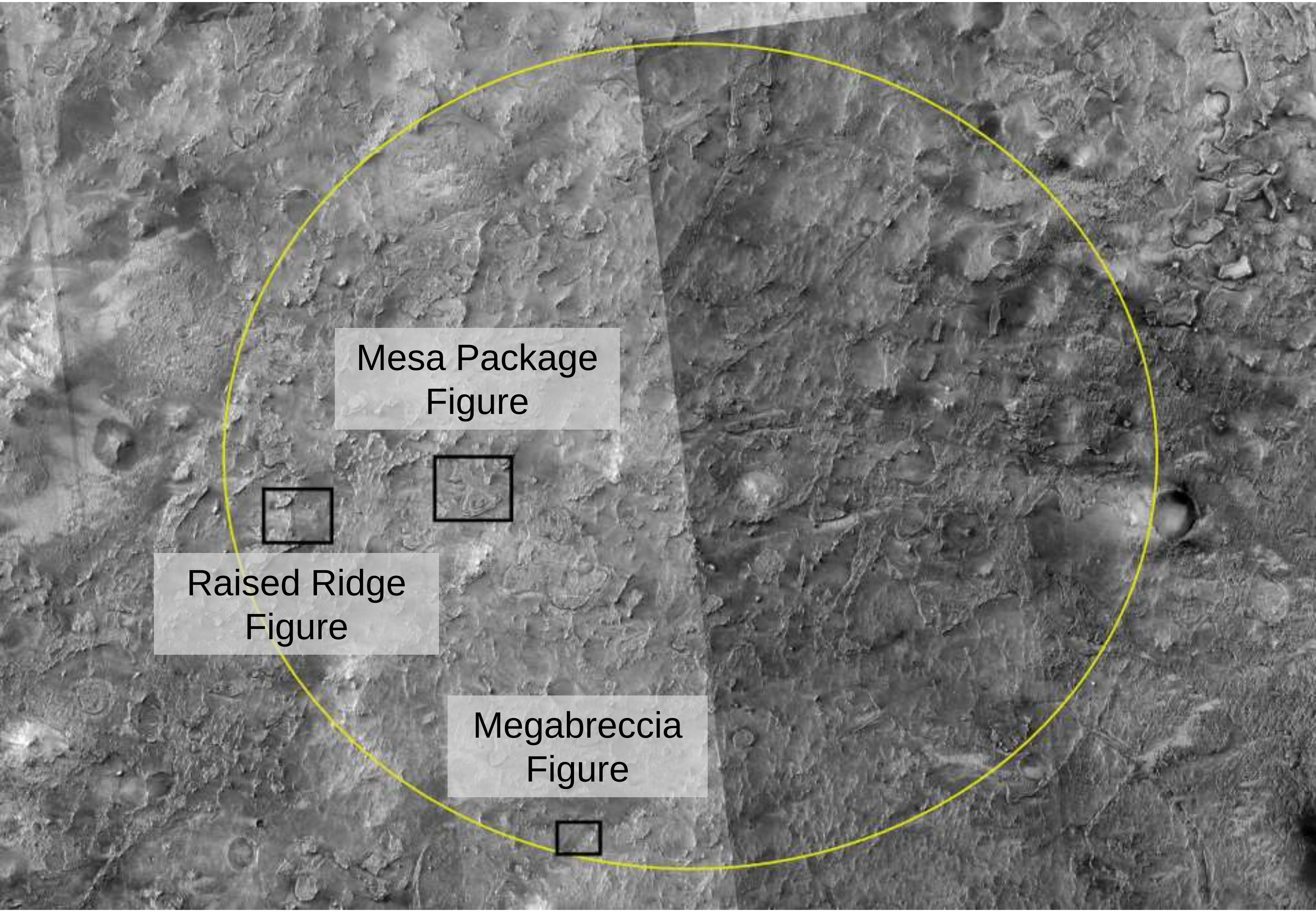
Noachian Crust: Megabreccia



Noachian Crust: No samples…yet*

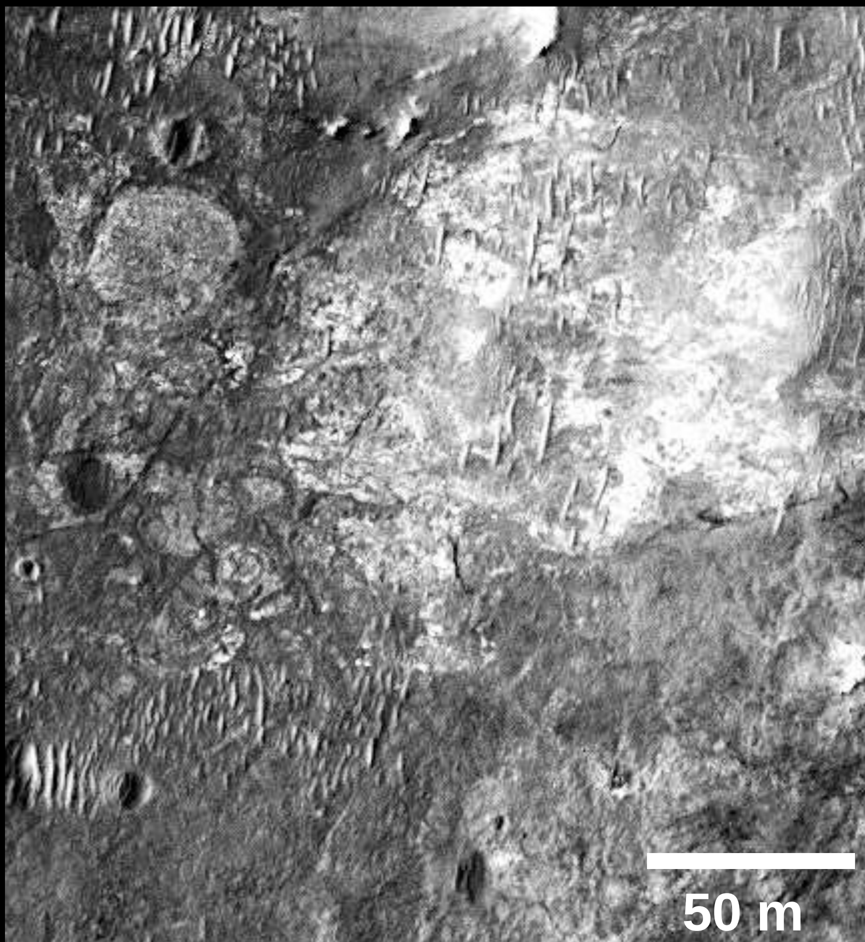
- Megabreccia uplifted and exposed by the Isidis Basin Forming event
  - Tap into Noachian rocks from the era of phyllosilicate formation:
  - Access to samples relevant to the deep biosphere:
  - Ancient, crystalline igneous crust:
  - Sample low-Ca pyroxene rich and other crystalline igneous rocks to constrain early crustal processes (Elkins-Tanton et al., 2005; 2012; Baratoux et al., 2011; Grott et al.,2013)
- Sample materials from the period during which Mars likely had
  - Magnetic field (Acuna et al., 1999),
  - Thicker atmosphere with different isotopic composition (Jakosky & Jones, 1997),
  - Pre-/during-the late heavy bombardment
- Highly relevant to the question "What governed the accretion, supply of water, chemistry, and internal differention of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large impact play?"

100 m


Mesa Package
Figure
Raised Ridge
Figure
Megabreccia
Figure

Noachian Basement:
In Ellipse Megabreccia

Hydrothermal (<100°C) surface	Hydrothermal (<100°C) subsurface
	~



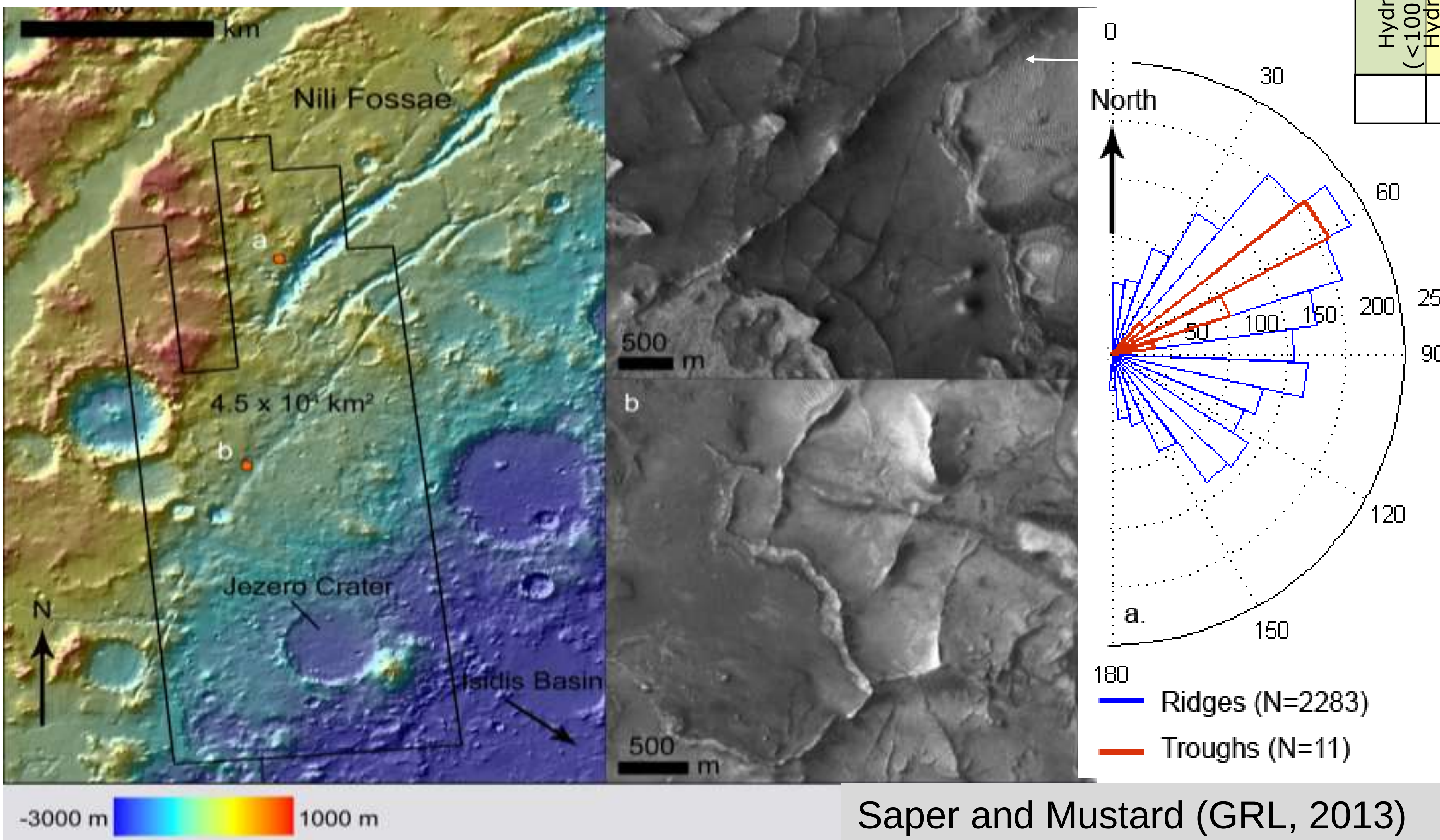
Widespread ridges in the Noachian crustal unit, 10s m wide, 100s m long

Morphology and Orientation of over 4000 Ridges suggest mineralized fracture zones

NE-SW orientation: Hydrothermal circulation in response to Isidis Impact?

Stratigraphically post-Isidis/pre-olivine/carbonate

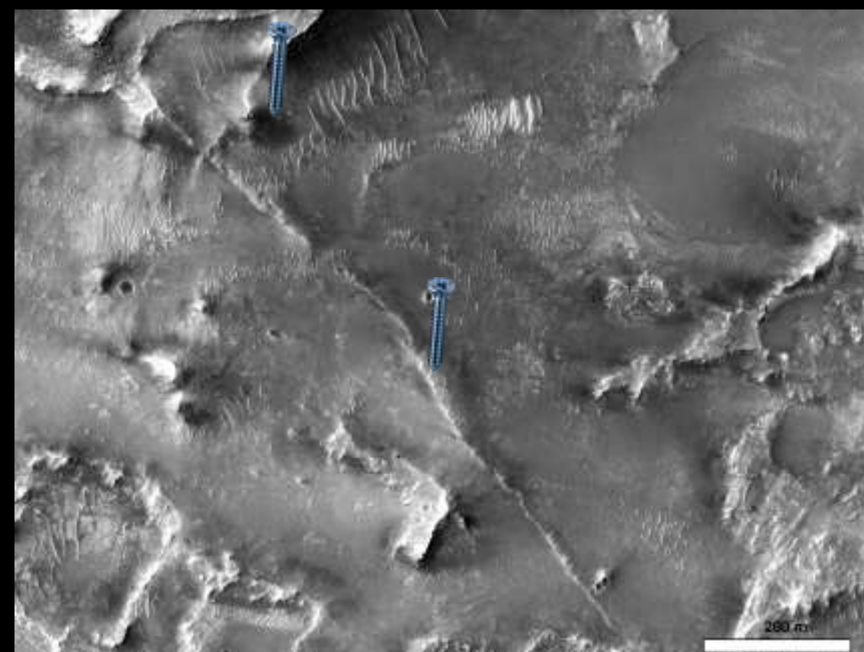
Hydrothermal (<100°C) surface	Hydrothermal (<100°C) subsurface
	~



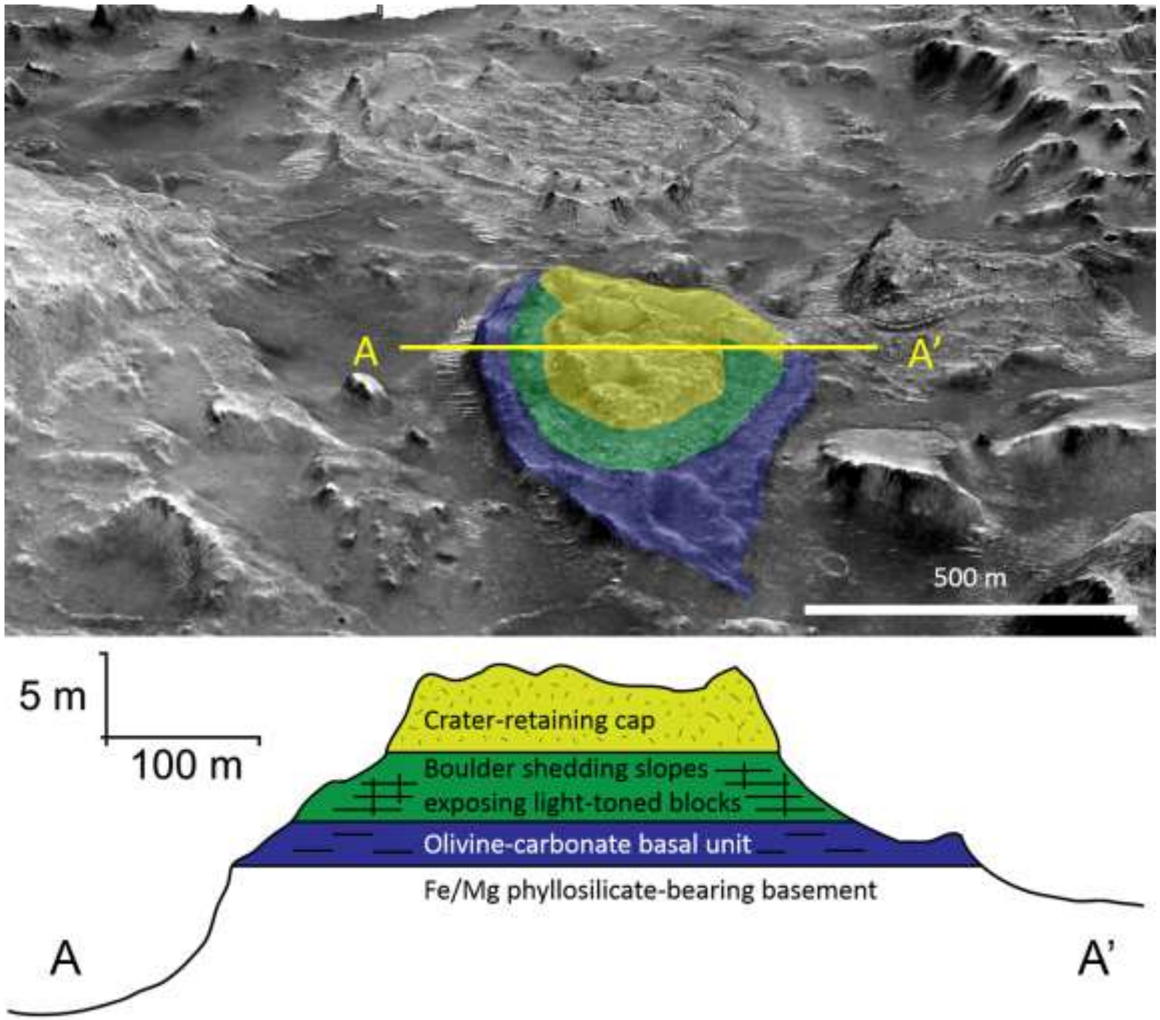
Saper and Mustard (GRL, 2013)

Noachian Basement:
In Ellipse Ridges

Hydrothermal (<100°C) surface	Hydrothermal (<100°C) subsurface
●	●



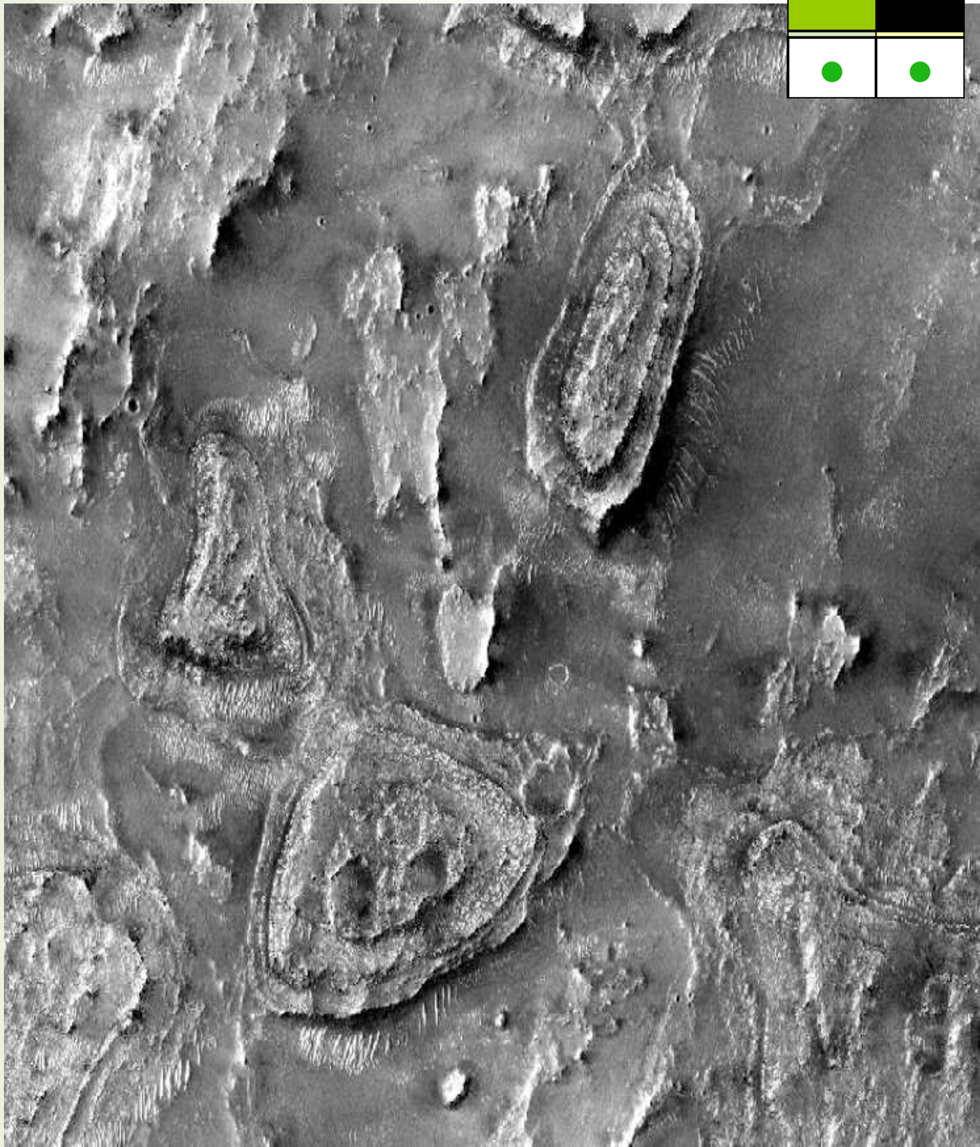
Mesa Package Stratigraphy

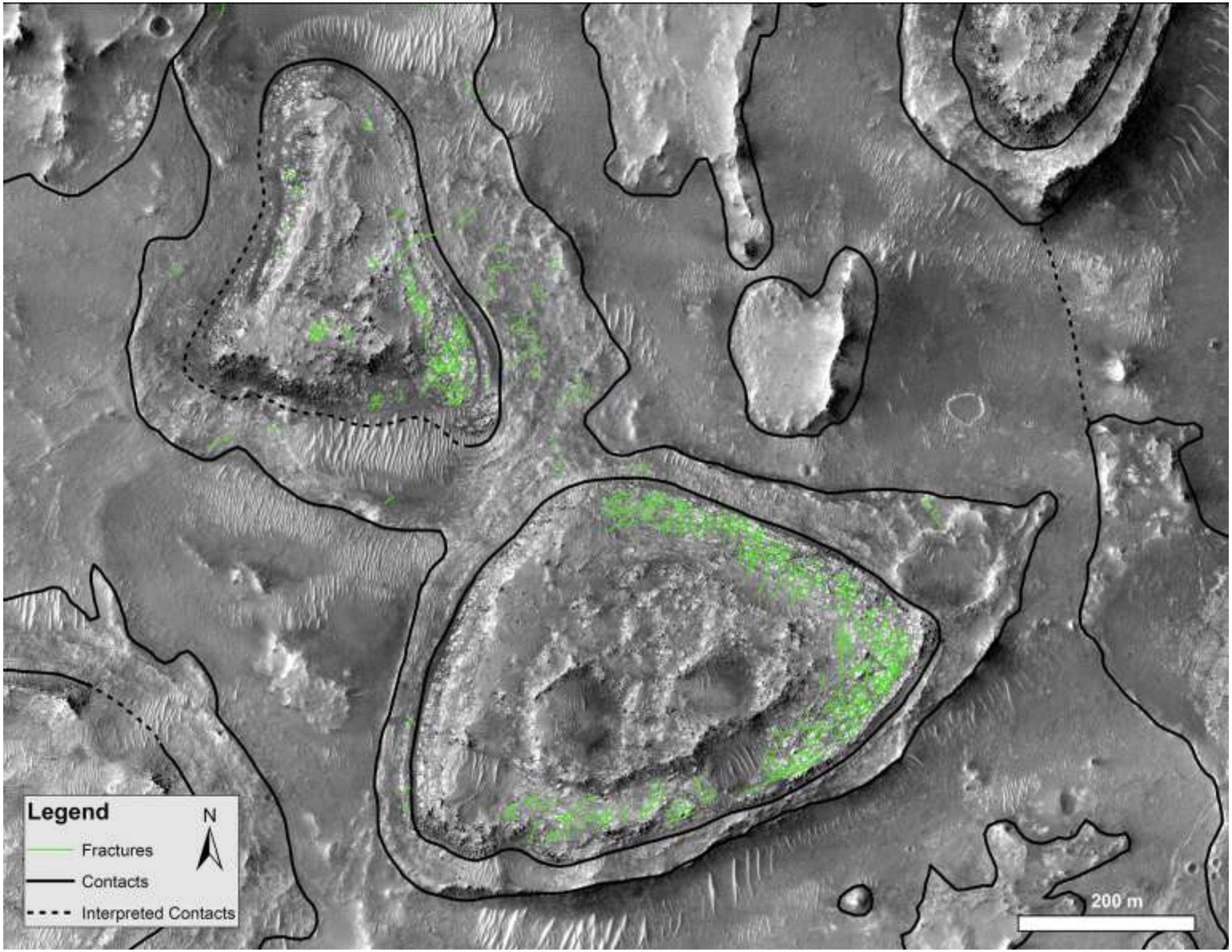


Topographic Profile from CTX DEM

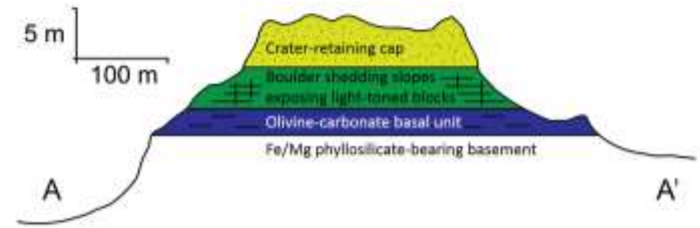
Mesa Forming Package

- Regional unit with three members
  - Crater retaining upper unit
  - Middle boulder shedding and slope forming unit
  - Lower unit that is banded, olivine bearing with variable carbonate
- Stratigraphically rests on basement of megabreccia and phyllosilicate
- Connected to many long, linear features with raised ridge borders, interiors of olivine-carbonate bearing materials
- Hypotheses:
  - Volcanic (Hamilton and Christensen, 2005; Tornabene et al., 2008)
    - Differentiated thick lavas
    - Sequence of volcanic flows from evolving source
  - Differentiated impact melt (Mustard et al., 2007; 2009)
- Olivine-bearing unit is a time-stratigraphic dateable unit!

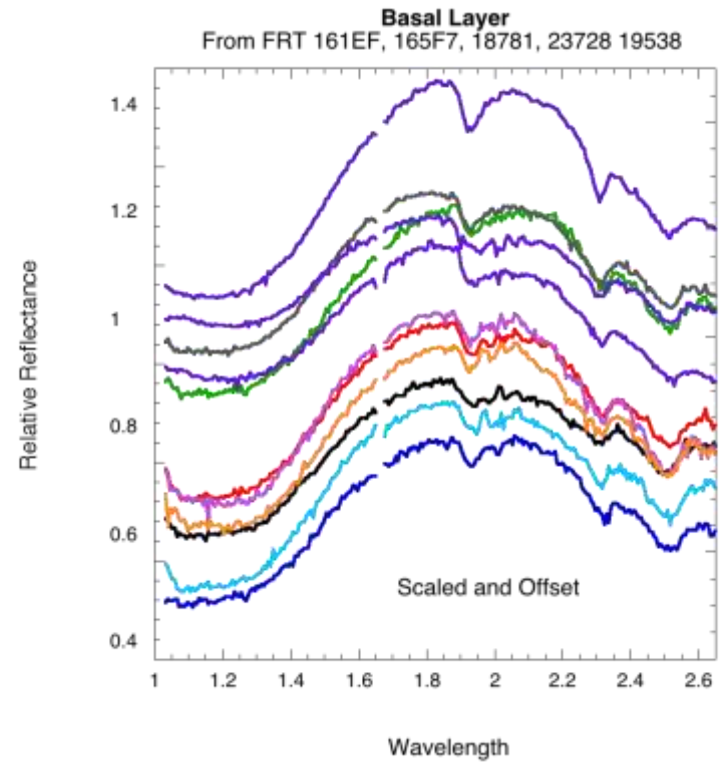



Legend
N
Fractures
Contacts
Interpreted Contacts
200 m

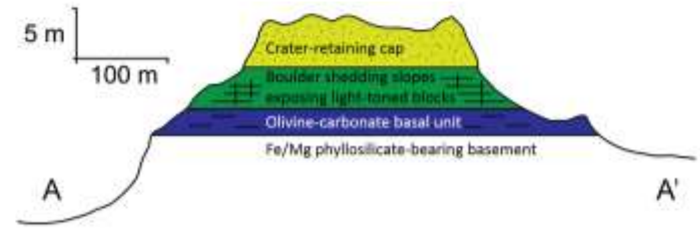
Spectroscopy/Mineralogy



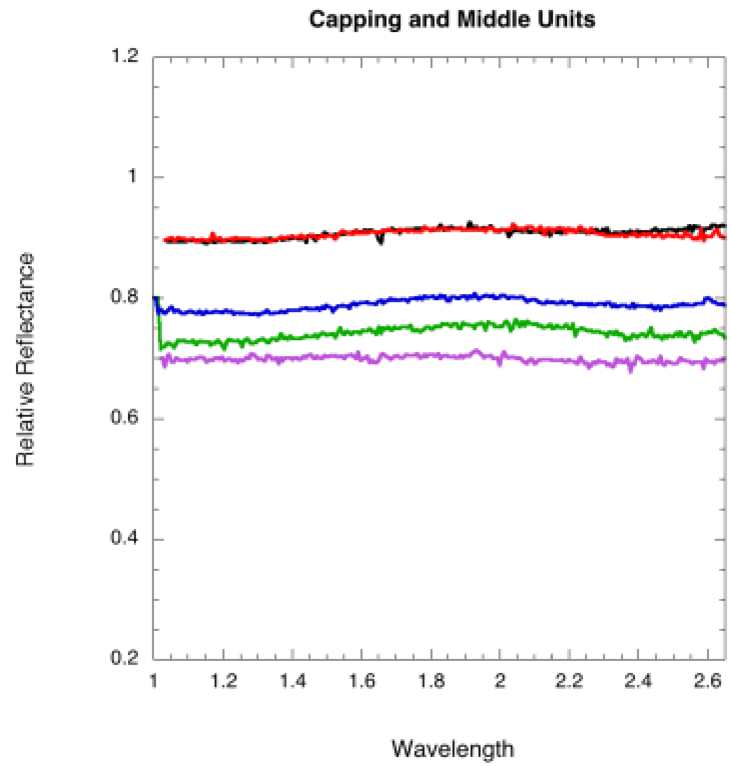
- Olivine-rich basaltic composition (Mustard et al., 2007; Edwards and Ehlmann 2015)
- Partially carbonated (Ehlmann and Mustard, 2012)
- Broad 1-1.6 μm absorption
- Paired 2.3 and 2.5 μm band indicative of carbonate
- 1.9 μm band of variable strength
- No 1.4 μm band
- Variable presence of a 2.38-2.39 band
  - Mixing with Fe-Mg phyllosilicate (Ehlmann et al., 2008, 2009)
  - Mixing with Talc (Viviano et al., 2013)



Spectroscopy/Mineralogy



- Capping and Middle units show weak mafic igneous absorptions near 1 and 2 µm
- Consistent with pyroxene and olivine, as modeled by Edwards and Ehlmann 2015
- Capping and Middle units distinguished by morphology and texture



Carbonation of olivine-rich rocks
Hypotheses

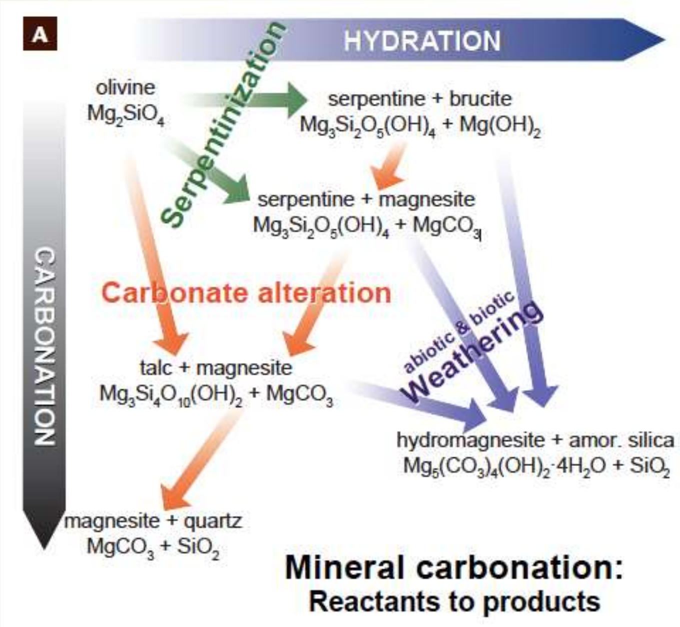
1) Water-rock interaction in the shallow subsurface at slightly elevated temperatures altered olivine to Mg-carbonate
2) Olivine-rich material, heated by impact or volcanic processes, emplaced on top of a water-bearing phyllosilicate rich unit initiated hydrothermal alteration along the contact
3) Olivine-rich rocks were weathered to carbonate at surface (cold) temperatures in a manner similar to olivine weathering of meteorites in Antarctica
4) Carbonate precipitated from shallow ephemeral lakes
5) Extended period of heat and water with burial leading to olivine-serpentine-talc-chlorite alteration pathway with carbonate from carbonation of serpentine (Brown et al., 2010; Viviano et al., 2013)

Unit of high value for environmental and astrobiological significance

Carbonation of Olivine

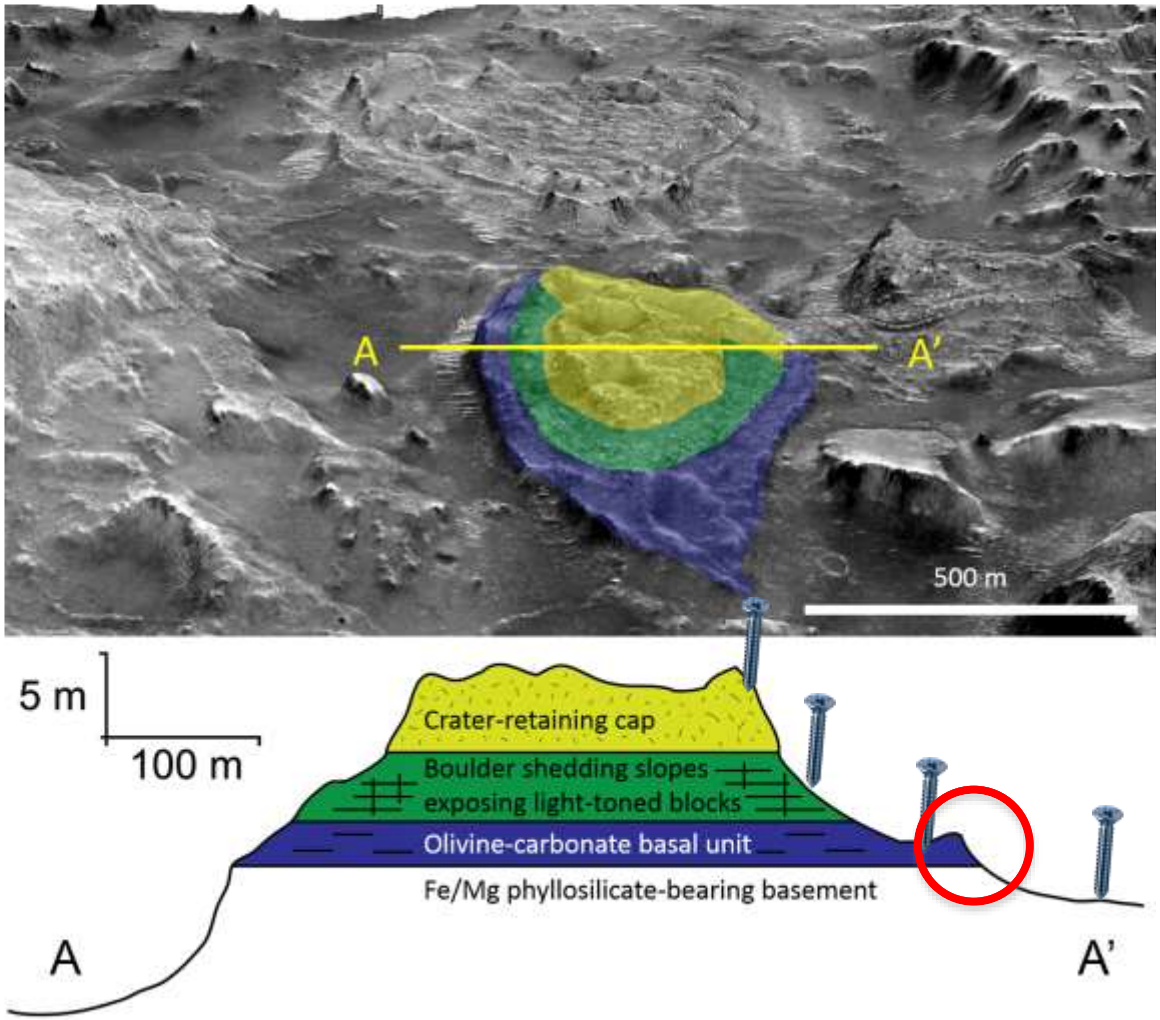
$$Mg_2SiO_4 + 2H_2O + 2CO_2 \rightarrow 2MgCO_3 + H_4SiO_4$$

- Multiple reaction pathways with different intermediate products (e.g. talc, serpentine) depending on diverse environmental constraints
- The direct pathway, observed in Oman, is energetically favorable and consistent with the geologic observations
- Carbonation of olivine is enhanced by multicomponent basalt (Sissman et al., 2014)
- Significant liberation of SiO_2: what is its fate?
- Assemblages, texture and context critical input to hypothesis testing



Power et al. (2013) DOI: 10.2113/gselements.9.2.115

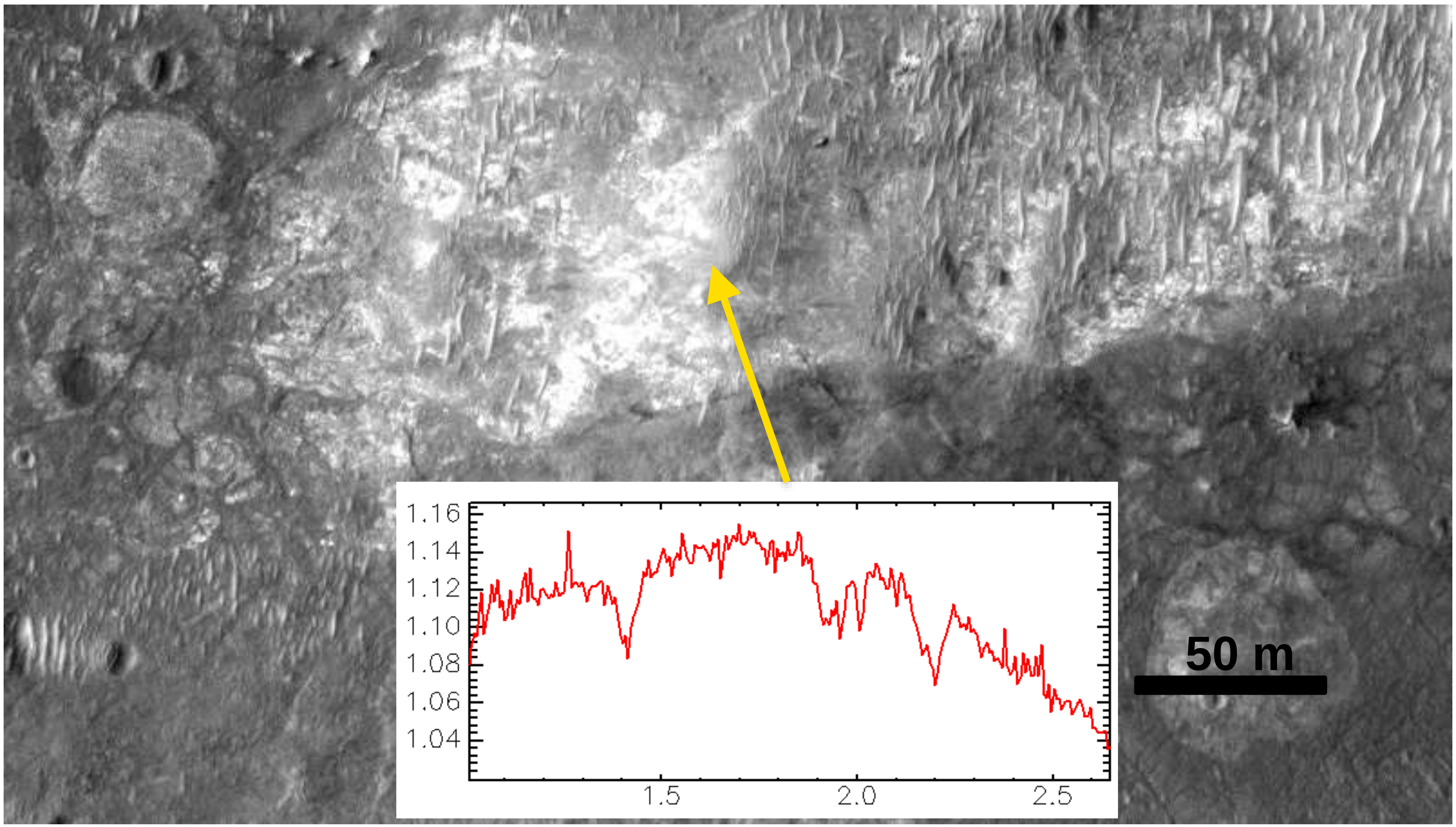
Mesa Package Stratigraphy



Topographic Profile from CTX DEM

basalt $\xrightarrow[\text{alteration}]{\text{partial}}$ Fe/Mg smectite $\xrightarrow[\text{loss of } Ca^{2+},\ Mg^{2+},\ Fe^{2+} \text{ ions}]{\text{enhanced leaching}}$ Kaolin group mineral $Al_2Si_2O_5(OH)_4$

(Analog: soil formation under intermittantly wet conditions, Hawaii, Italy)

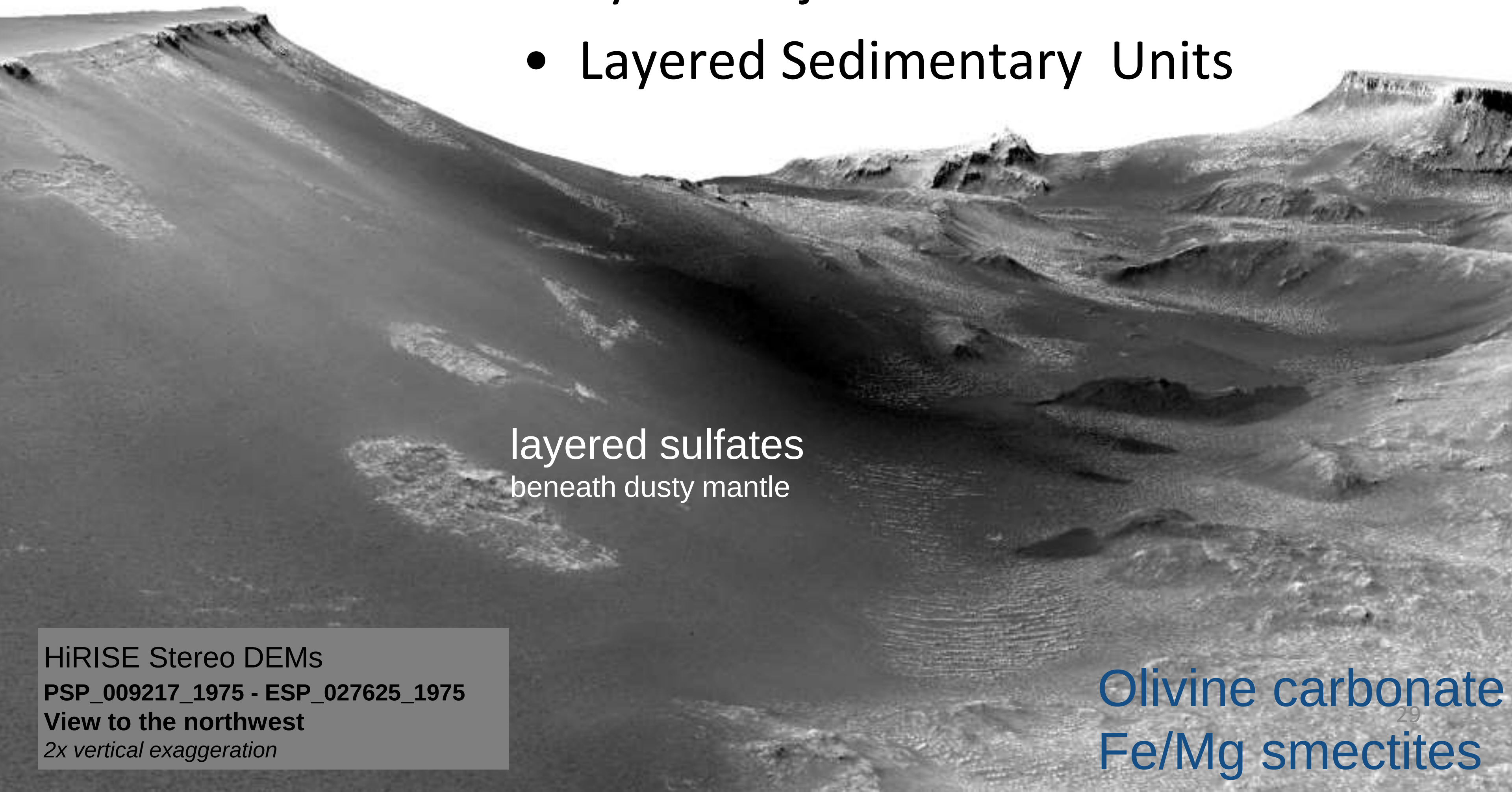


Kaolinite-smectite alteration *occurs where precursor rock is not olivine-rich (pyx, Fe/Mg smectite)*

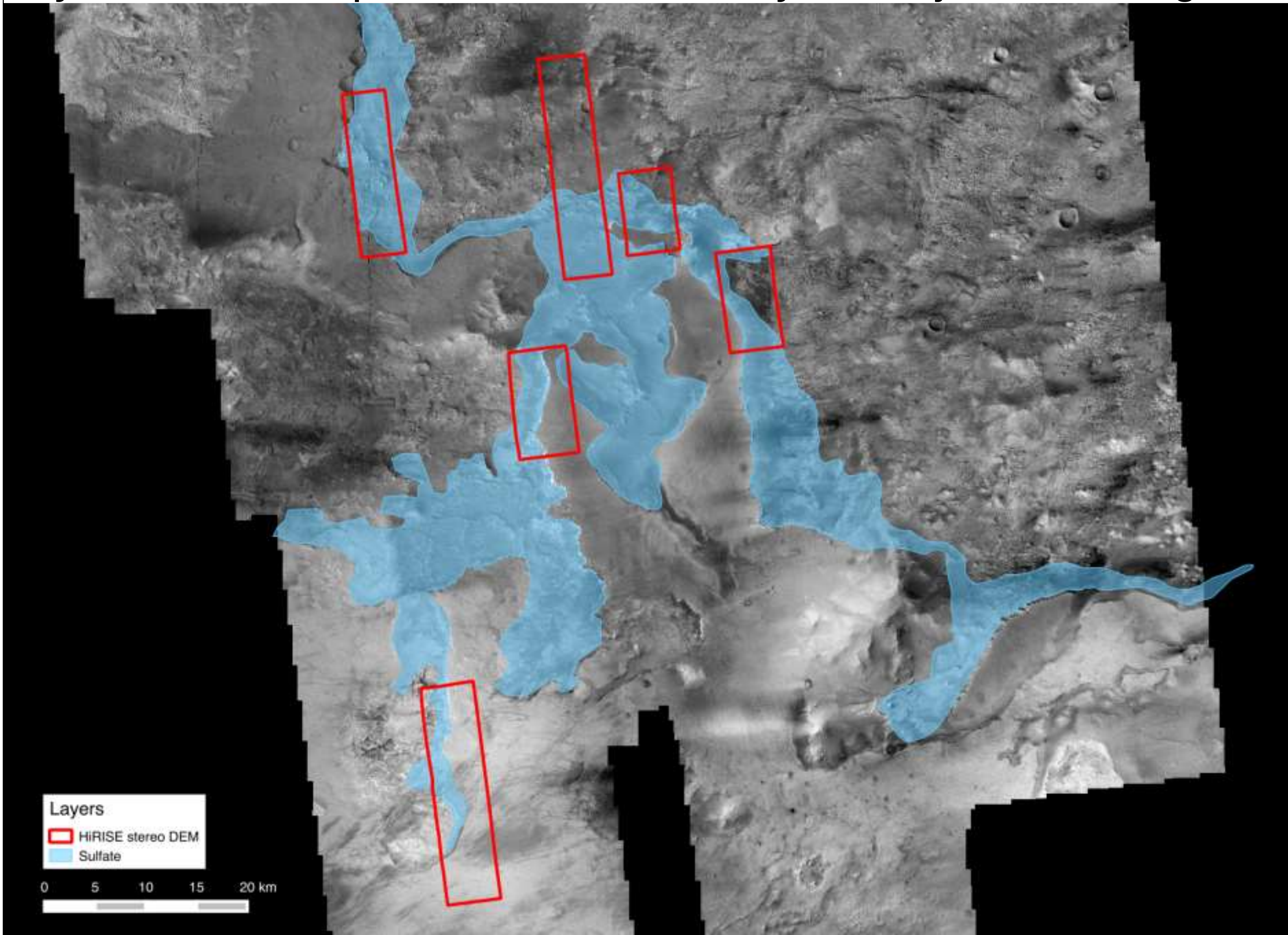
Bonus, Out of Ellipse Science

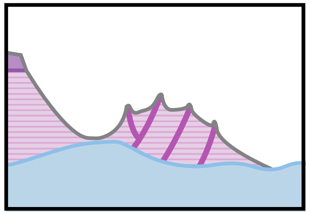
- Significant Sulfate Deposits
- Syrtis Major Lavas
- Layered Sedimentary Units

Syrtis Major lavas



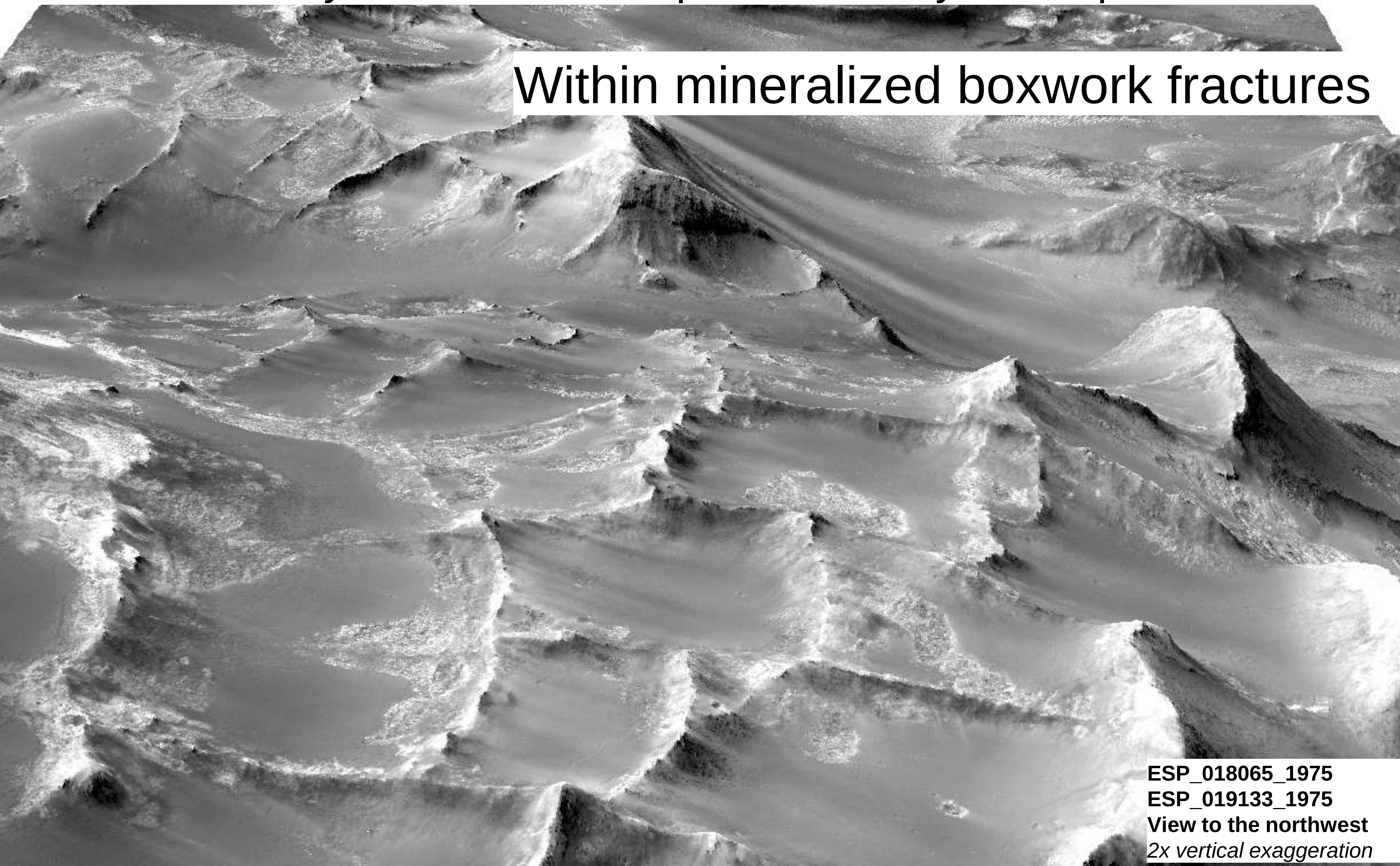
Layered sulfates preserved beneath Syrtis Major flow margin



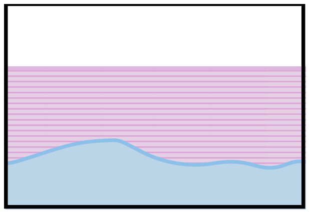


5. Differential erosion

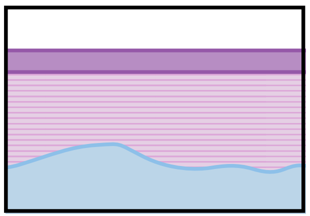
Layered sulfates are preserved only where protected



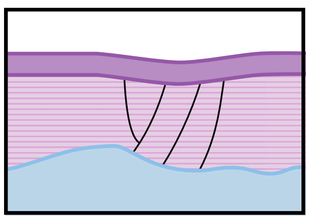
Layered sulfate chronology



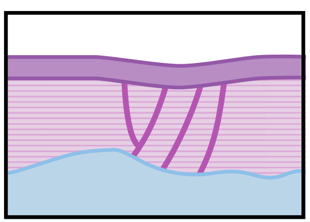
1. Deposition as flat-lying sediments



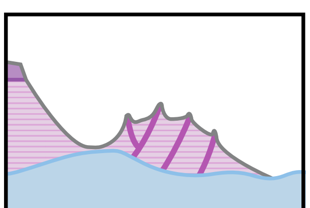
2. Burial by lava *(± other sediments)*



3. Diagenesis and volume-loss fracturing



4. Fluid mineralization along fractures



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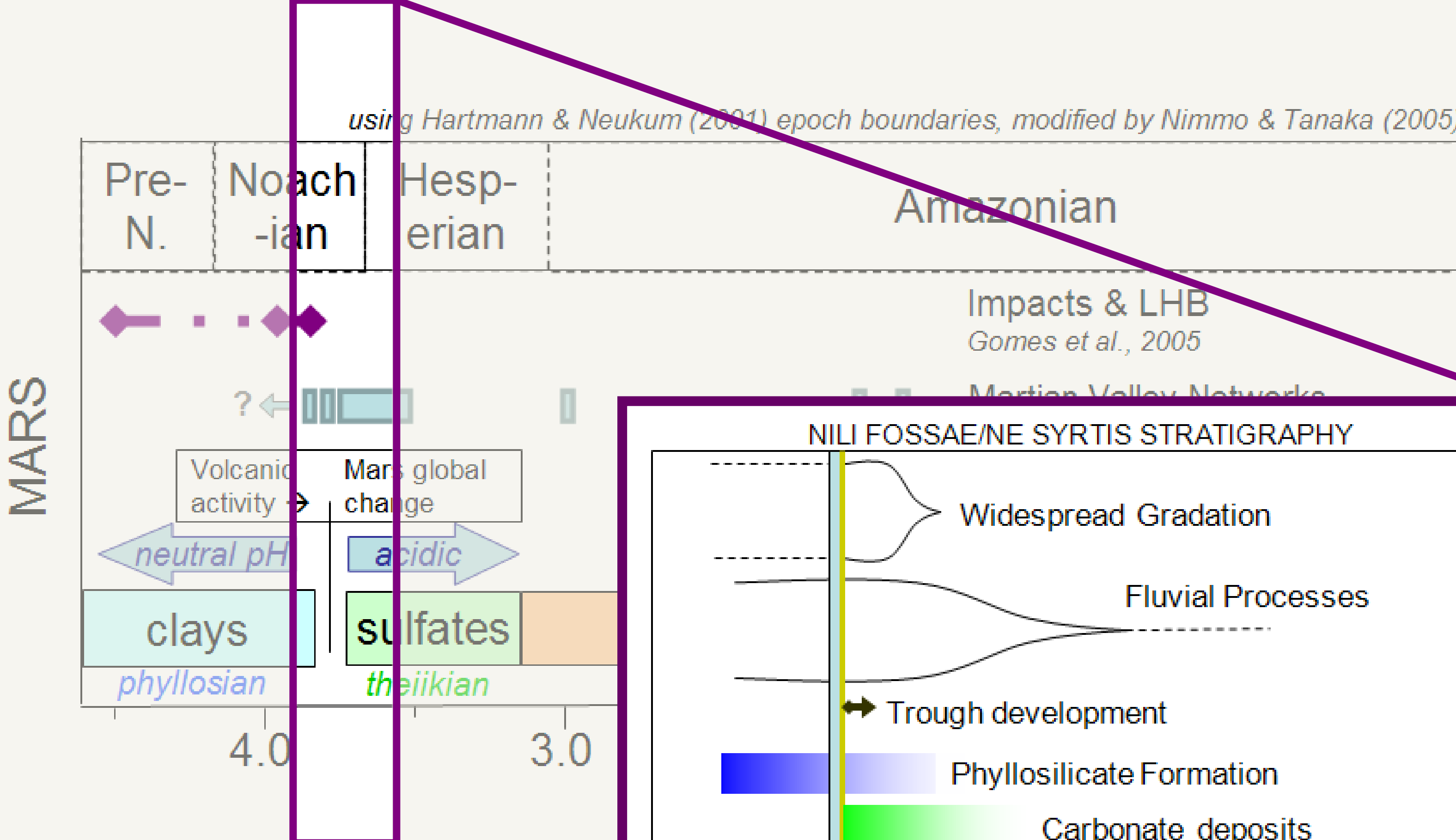

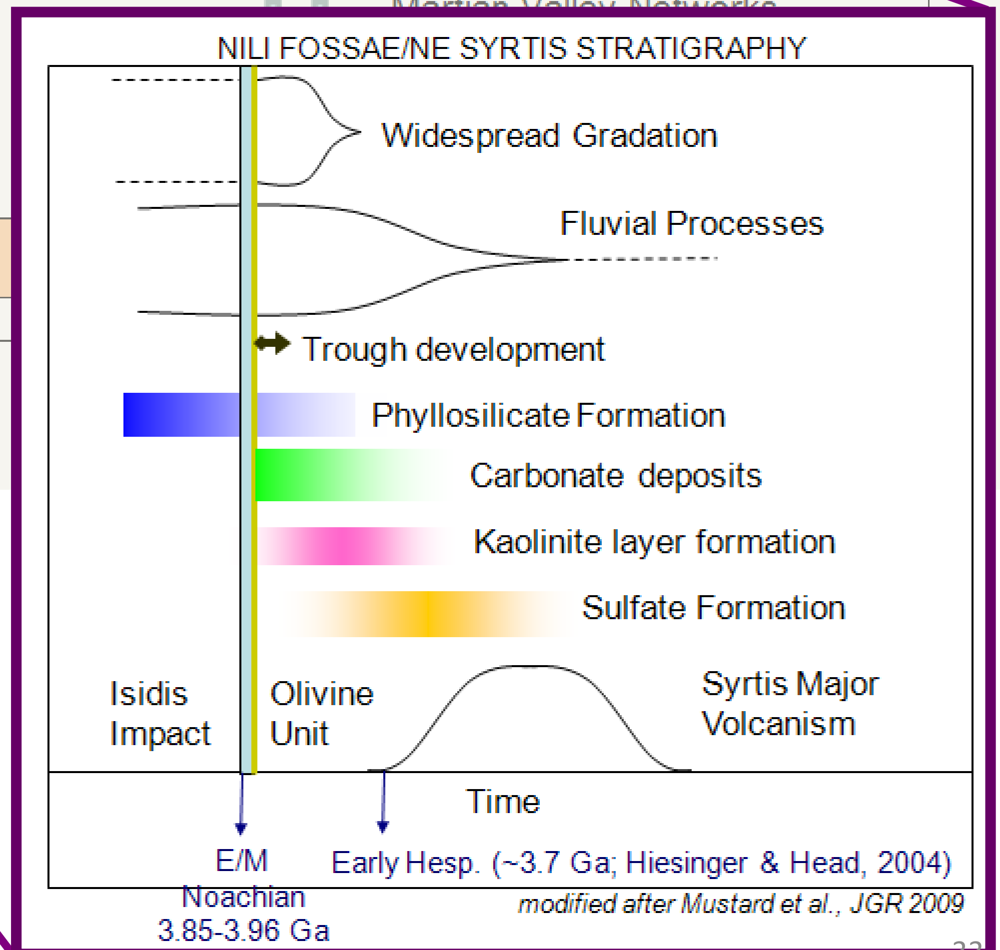

Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian

Conclusions

- Target-rich in ellipse science; go-to science traverses Noachian to Hesperian
- Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  - early crustal: creation or distribution by impact
  - carbonate/serpentine: surface alteration or hydrothermal?
  - layered phyllosilicates (Al- over Fe/Mg): from leaching with surface hydrology?
  - (sedimentary?) acid sulfate formation
- A record of aqueous geochemistry preserved in-situ, in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting well-suited for the M2020 instrument suite
- Key stratigraphies, dateable from Noachian to Hesperian eras: does this capture Mars global environmental change?

Compelling Mars and Astrobiology Science

- Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  - early crustal: creation or distribution by impact? Phyllosilicate formation
  - carbonate/serpentine: surface alteration or hydrothermal?
  - layered phyllosilicates (Al- over Fe/Mg)
  - sedimentary sulfate formation
- A record of aqueous low-T geochemistry preserved in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting
- Well-suited for the M2020 measurements and caching
- Key stratigraphies from Noachian and Hesperian eras
- Hydrothermal, pedogenic and sedimentary environments
- Multiple igneous units of distinct age

Landing Site Factor	Mars 2020 Mission and Decadal Priority Science Factors																							
	Environmental Setting for Biosignature Preservation and Taphonomy of Organics								Type 1A & 1B Samples: Aqueous Geochemical Environments indicated by Mineral Assemblages									Type 2 Samples: Igneous		Context: Martian History Sampled, Timing Constraints				
	Deltaic or Lacustrine (perennial)	Lacustrine (evaporitic)	Hydrothermal (<100°C) surface	Hydrothermal (<100°C) subsurface	Pedogenic	Fluvial/Alluvial	No diagenetic overprinting	Recent exposure	Crustal phyllosilicates	Sedimentary clays	Al clays in stratigraphy	Carbonate units	Chloride sediments	Sulfate sediments	Acid sulfate units	Silica deposits	Ferric Ox./Ferrous clays	Igneous unit (e.g, lava flow, pyroclastic, intrusive)	2nd Igneous unit	Pre- or Early-Noachian Megabreccia	Oldest stratigraphic constraint	Youngest stratigraphic constraint	Stratigraphy of units well-defined	Dateable surface, volcanic (unmodified crater SFD)
NE SYRTIS			~	~	●	○	~	●	●		●	●		○	○			●	○	●	LN	H	●	●

Mars 2020 Rubric

Landing Site Factor	Mars 2020 Mission and Decadal Priority Science Factors																							
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NE SYRTIS			~	~	●	○	~	●	●		●	●		○	○			●	○	●	**LN**	**H**	●	●

Saper and Mustard, 2013

Mangold et al, 2008; Fassett et al, 2009; Skok et al., 2013

Mustard, 2007; 2009, Ehlmann 2009; 2011, Brown 2010; Viviano 2013, Ehlmann and Mustard, 2011

Mustard, 2007; 2009, Ehlmann 2009; 2011, Mangold el al, 2007; Viviano 2013, Ehlmann and Mustard, 2011

Ehlmann 2009; 2011, Ehlmann and Mustard, 2011

Mustard, 2007; 2009, Ehlmann 2009; 2011, Mangold el al, 2007; Viviano 2013, Ehlmann and Mustard, 2011; Michalski et al., 2010 +++

Mustard et al, 2007; 2009; Tornabene, et al. 2007;

Baratoux et al., 2007, 2011; Skok et al., 2010; Heisinger and Head, 2003; Clenet et al., 2013; +++

Mustard et al, 2007; 2009

Backup And Extras

4 Unprioritized ROI’s

Landing Site and Engineering Constraints

- Target-rich in ellipse science; go-to traverses Noachian to Hesperian
- Key hypotheses addressed in the ellipse with M2020 measurements and caching

Center Coordinates	• 17.84° N 77.15° W
Elevation	• -2000 m WRT MOLA geoid
Prime Science and/or Sampling Targets	• Olivine-carbonate assemblage • Isidis (?) megabreccia with phyllosilicate and unaltered igneous outcrops • Layered kaolinite-bearing capping stratigraphy • Mineralized fracture zones • Hesperian-aged Sulfate stratigraphy • Hesperian Syrtis Major volcanics (lowest priority)
Distance of Science and/or sampling targets from Ellipse Center	• In Ellipse targets are typically 3-5 km from the ellipse center (olivine-carbonate outcrops, megabreccia, mineralized fracture zones, layered stratigraphies) • Hesperian targets (sulfate stratigraphy and Syrtis volcanics) are outside the ellipse

Major Hypotheses to be Tested

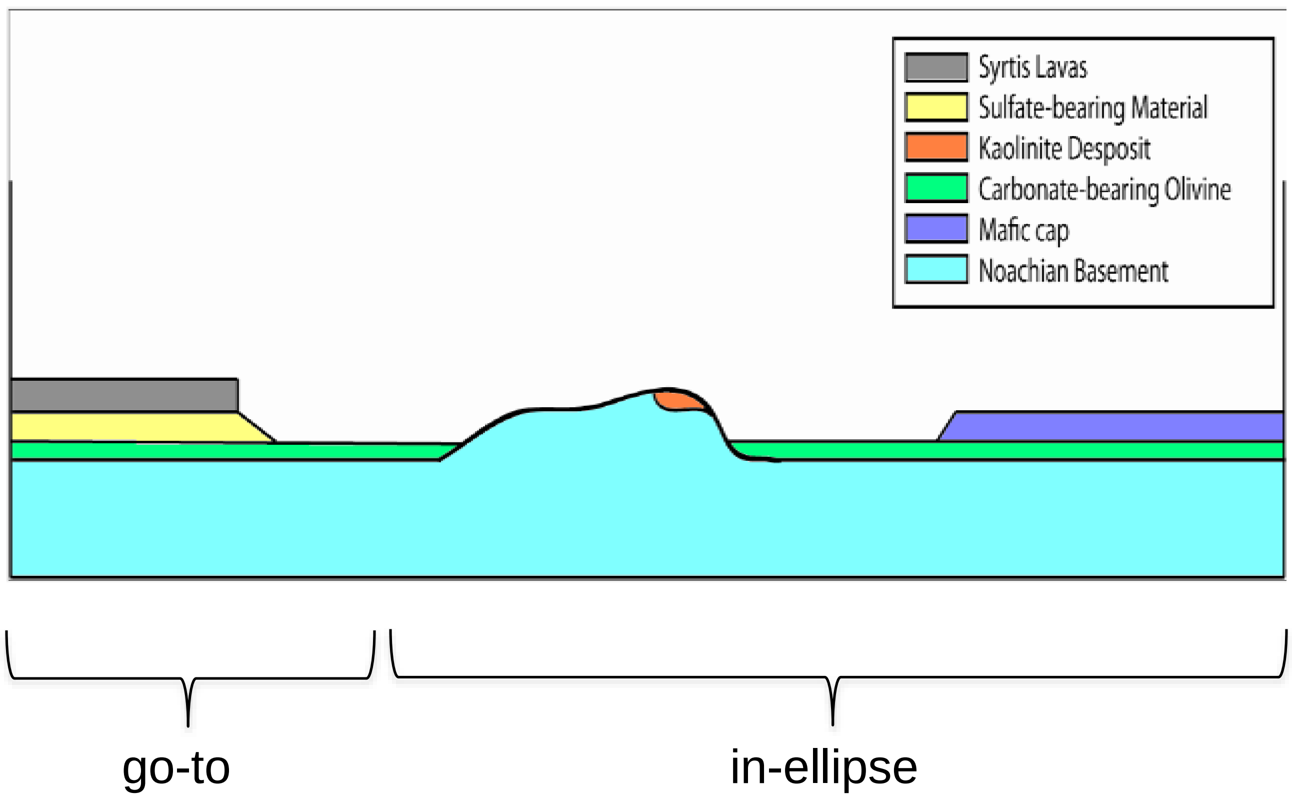
Olivine-bearing regional unit	• Ultramafic volcanic emplaced post-Isidis • Ultramafic impact melt from Isidis that tapped the mantle
Olivine-Magnesite Mineral Assemblage	• Near-surface weathering • Serpentinizing hydrothermal systems • Aqueous alteration in a metamorphic setting • Sedimentary/lacustrine deposits within ultramafic catchments
kaolinite-bearing capping stratigraphy:	• Extensive leaching during a period of vertically integrated water cycle
Erosionally resistant ridges	• Fracture zones mineralized with hydrothermal sediments • Volcanic dikes • Breccia dikes
Hesperian-aged Sulfate stratigraphy	• Deposition as flat lying sediments • Extensive dewatering and mineralization of fractures
Hesperian Syrtis Major volcanics	• Calibration of crater chronology, testing the formation mechanism (chemistry and mineralogy), validating remote sensing

Megabreccia with phyllosilicate and unaltered igneous outcrops	• Phyllosilicate in megabreccia: Low-T, low water/rock ratio alteration in the shallow crust
	• Unaltered igneous outcrops
	    • Remnants of Mars primary crust
	    • Noachian-aged low-Ca pyroxene lavas

Examples of the Strength of MSL Instrument To Address the Hypotheses

Olivine-bearing regional unit	• Ultramafic volcanic emplaced post-Isidis • Ultramafic impact melt from Isidis that tapped the mantle • Mastcam-Z Context geology • Supercam: Reconnassiance and close-in major element chemistry LIBS VNIR mineral spectroscopy of ferrous igneous mineralogy to derive olivine Fe/Mg ratios Raman to determine context and close up mineralogy • PIXEL: Detailed elemental chemistry among mineral phases to resolve textures • SHERLOC: Discriminate detailed mineralogic associations
Olivine-Magnesite Mineral Assemblage	• Supercam: Context and close-up aqueous mineralogy with VNIR Spectroscopy and RAMAN • PIXEL Detailed mineralogy among minerals to determine assemblages • SHERLOC Discriminate detailed mineralogic associations

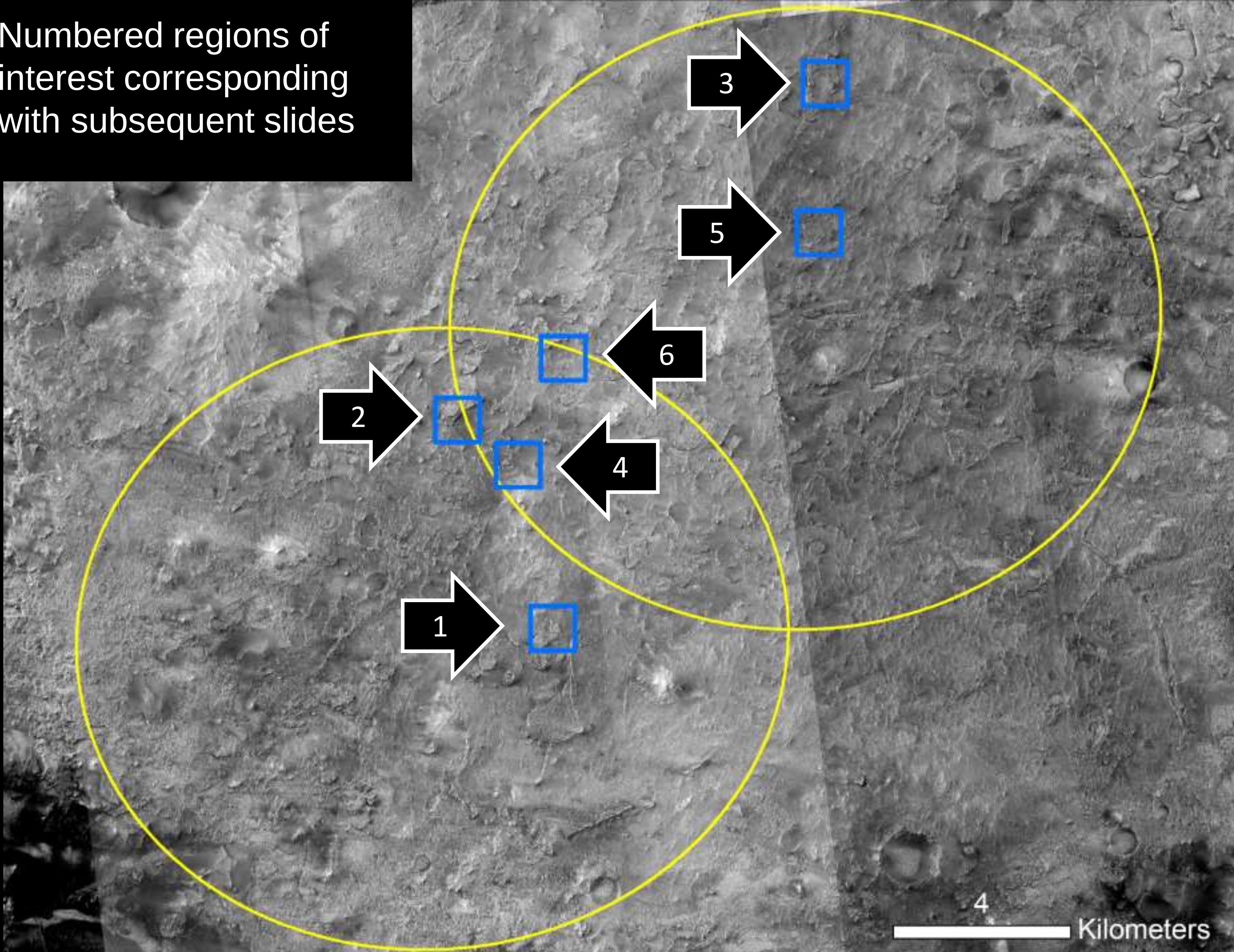
Regional Stratigraphy provides the context for in-ellipse and go-to science



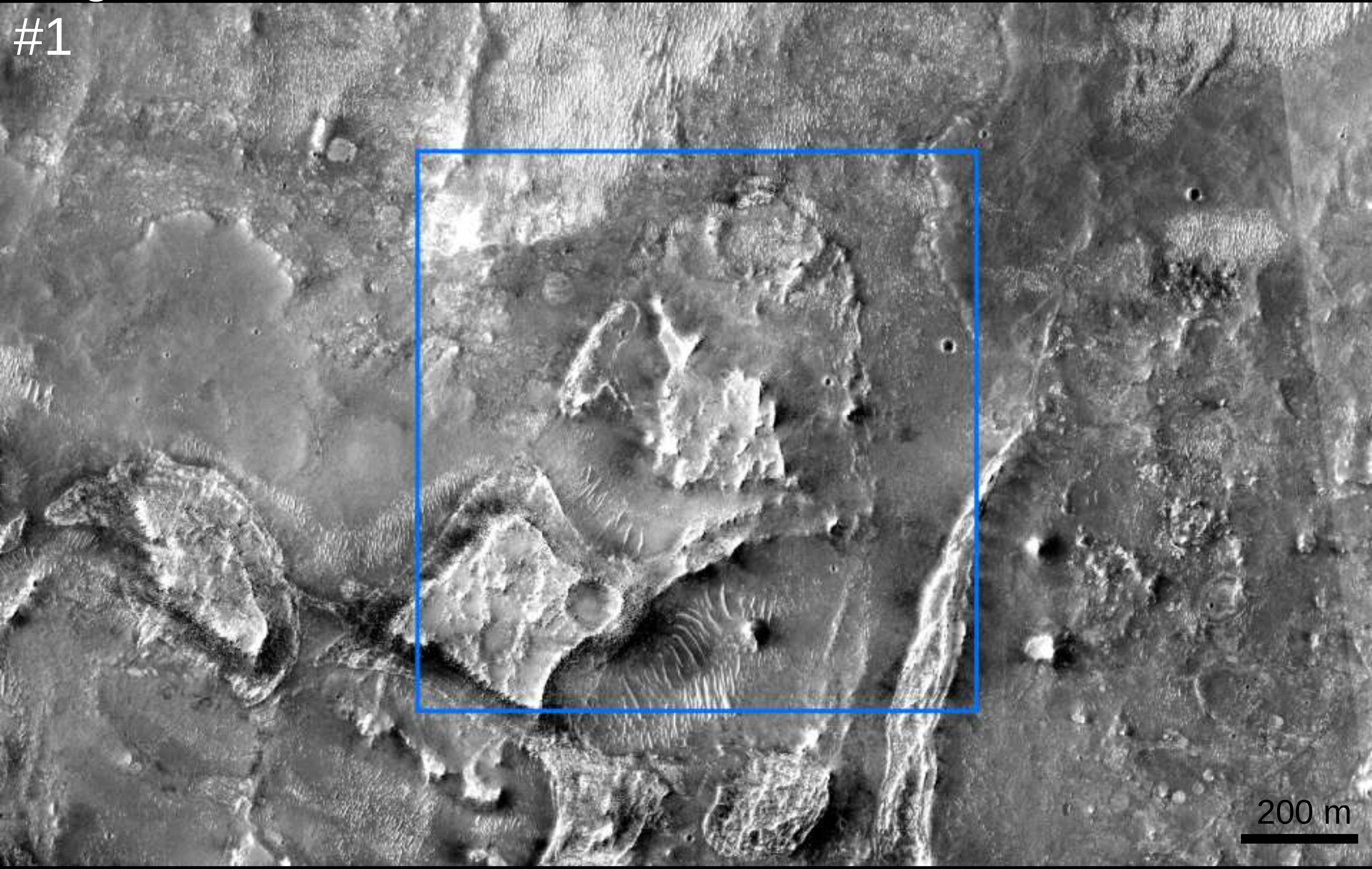
Regions of Interest

- Target rich landing ellipse provides innumerable targets of interest, and we show 4 here
- Easily accomplish 90% of landing site goals in these 3 ROIs

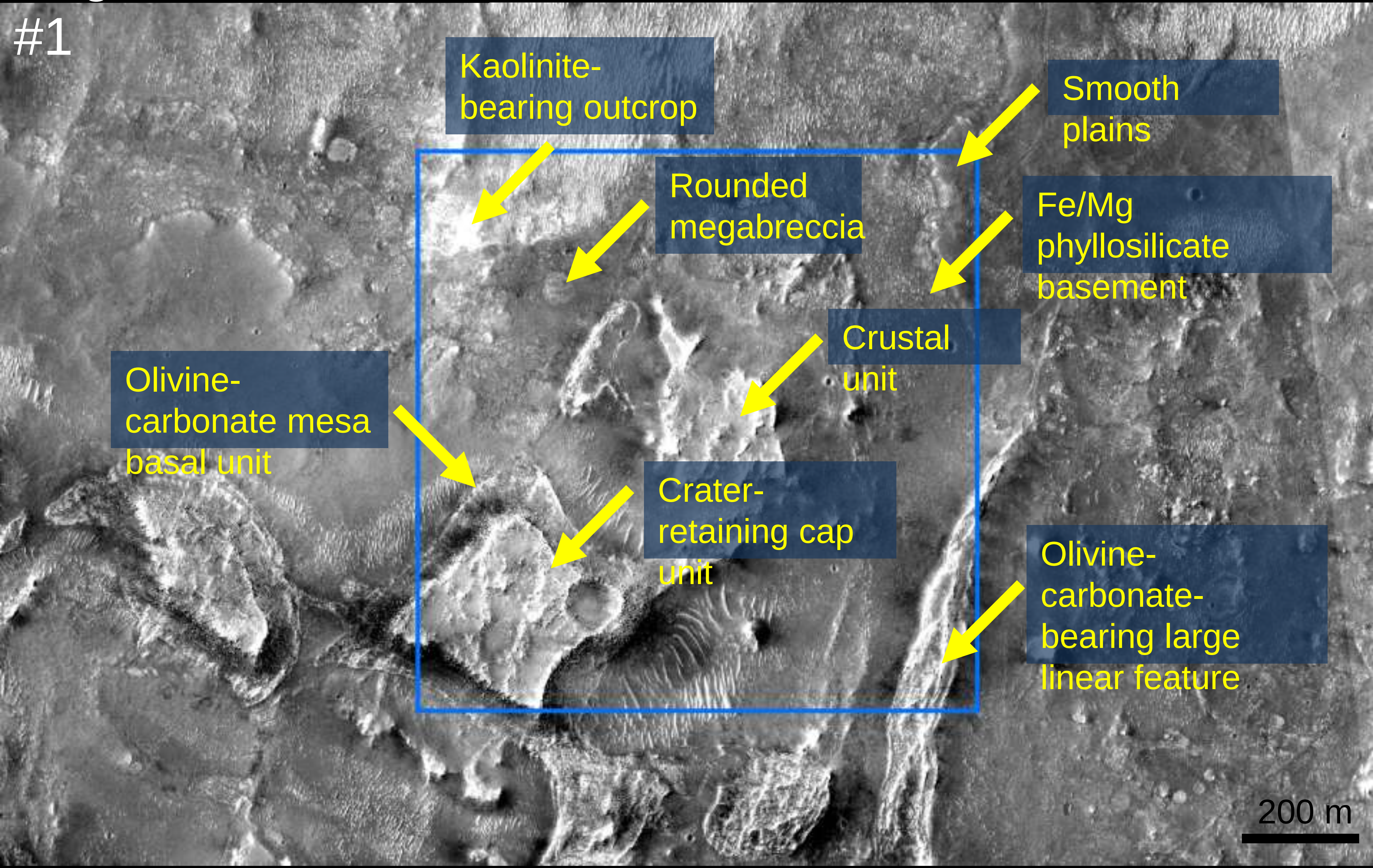
Numbered regions of interest corresponding with subsequent slides



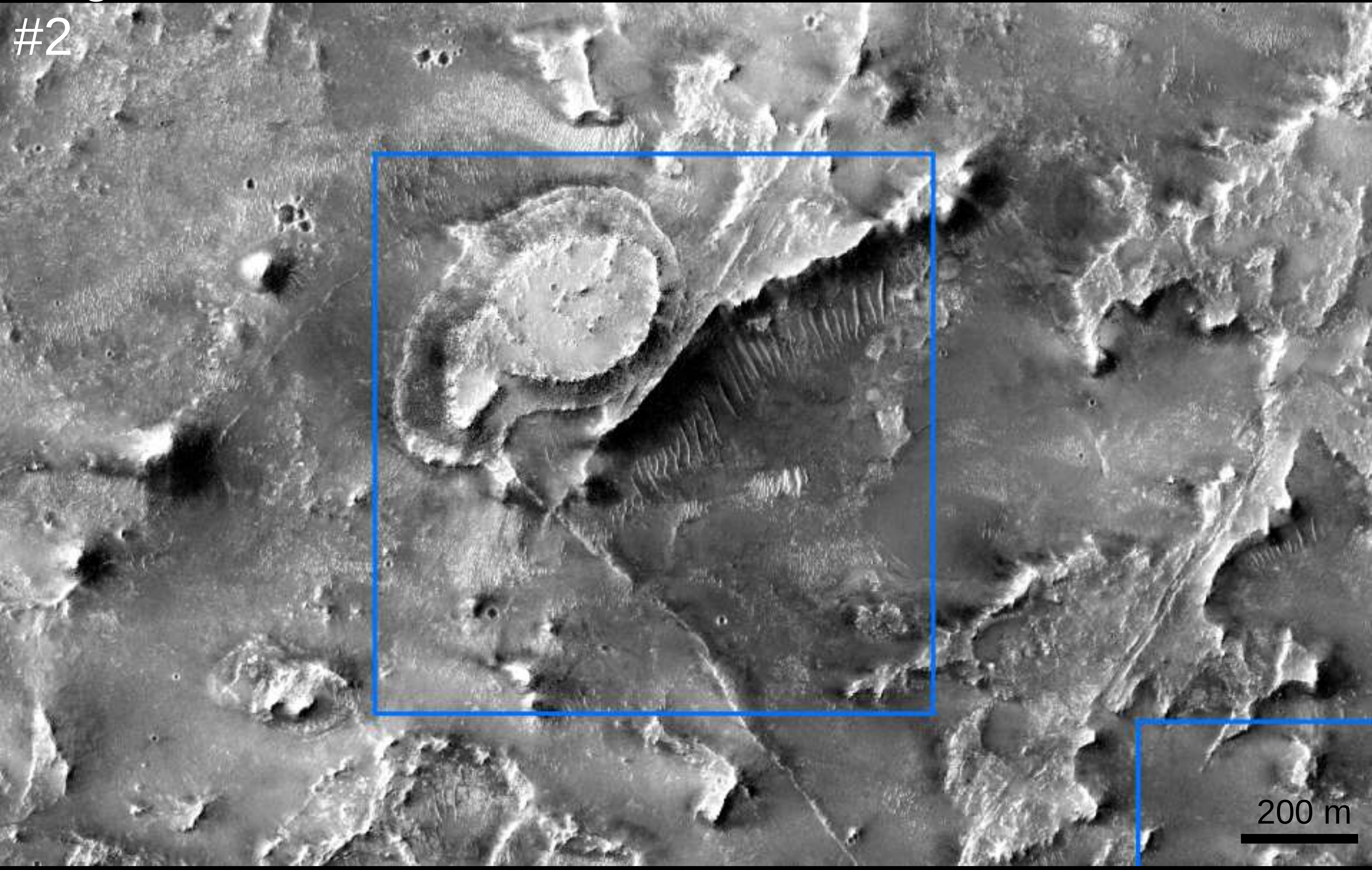
Region of Interest



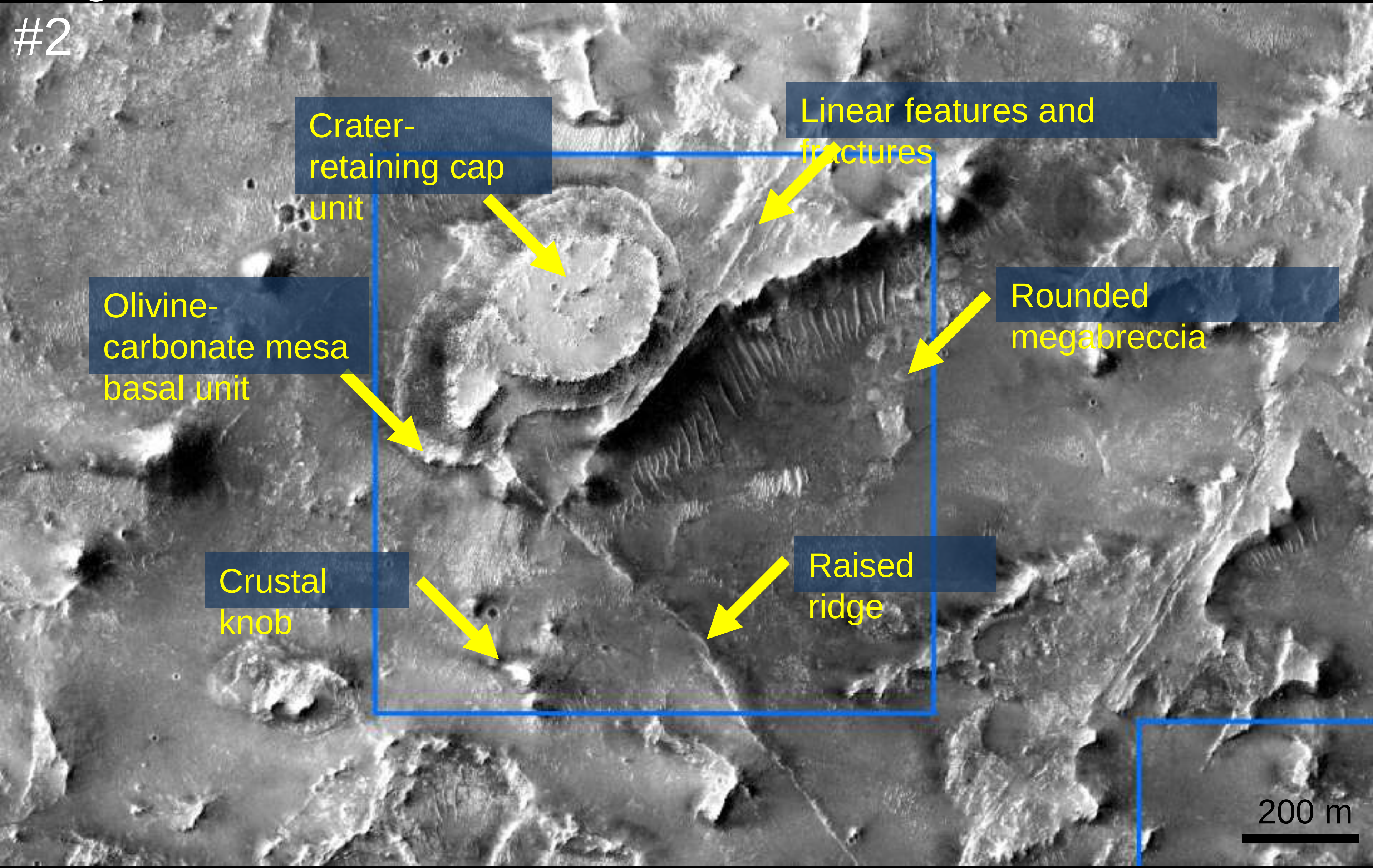
Region of Interest



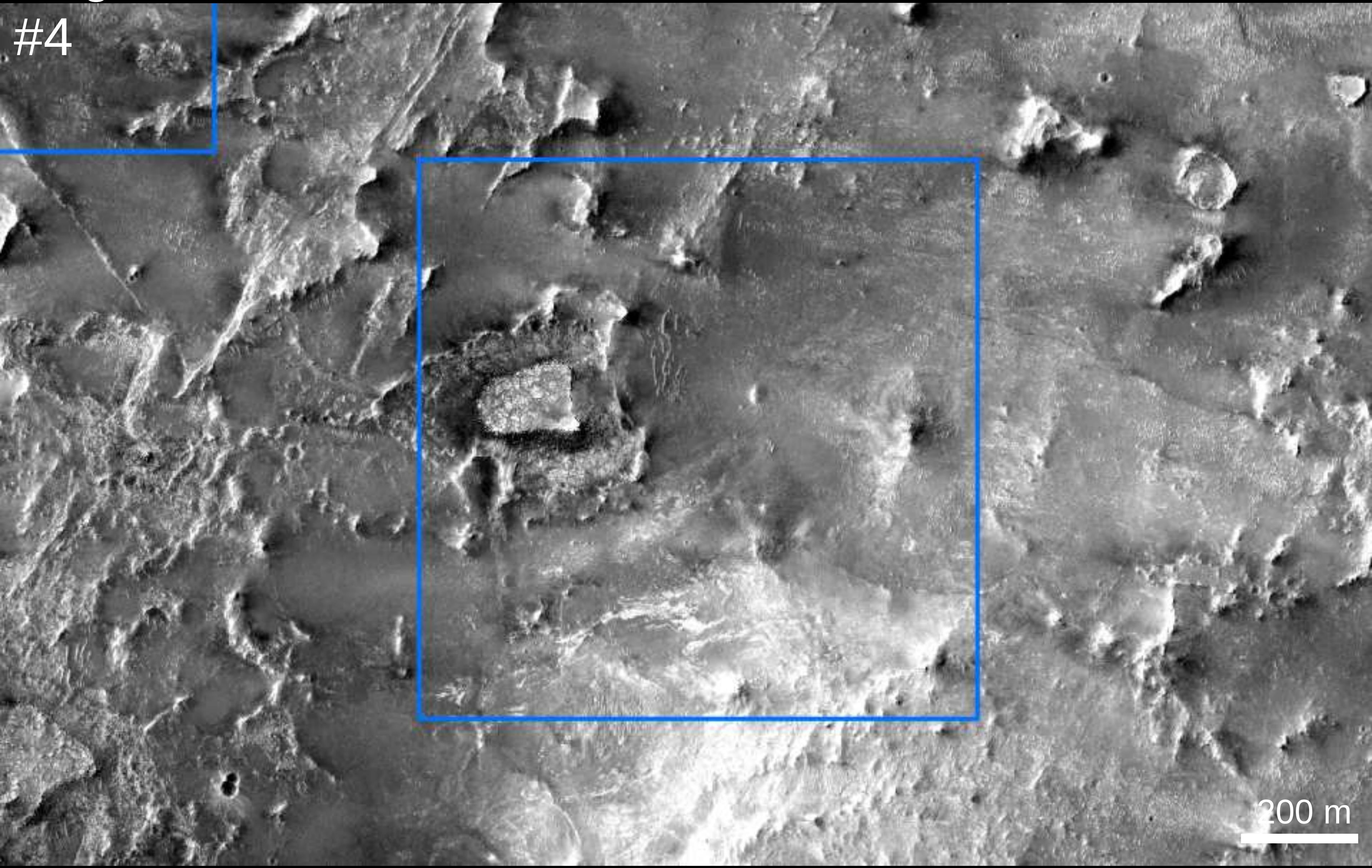
Region of Interest #2



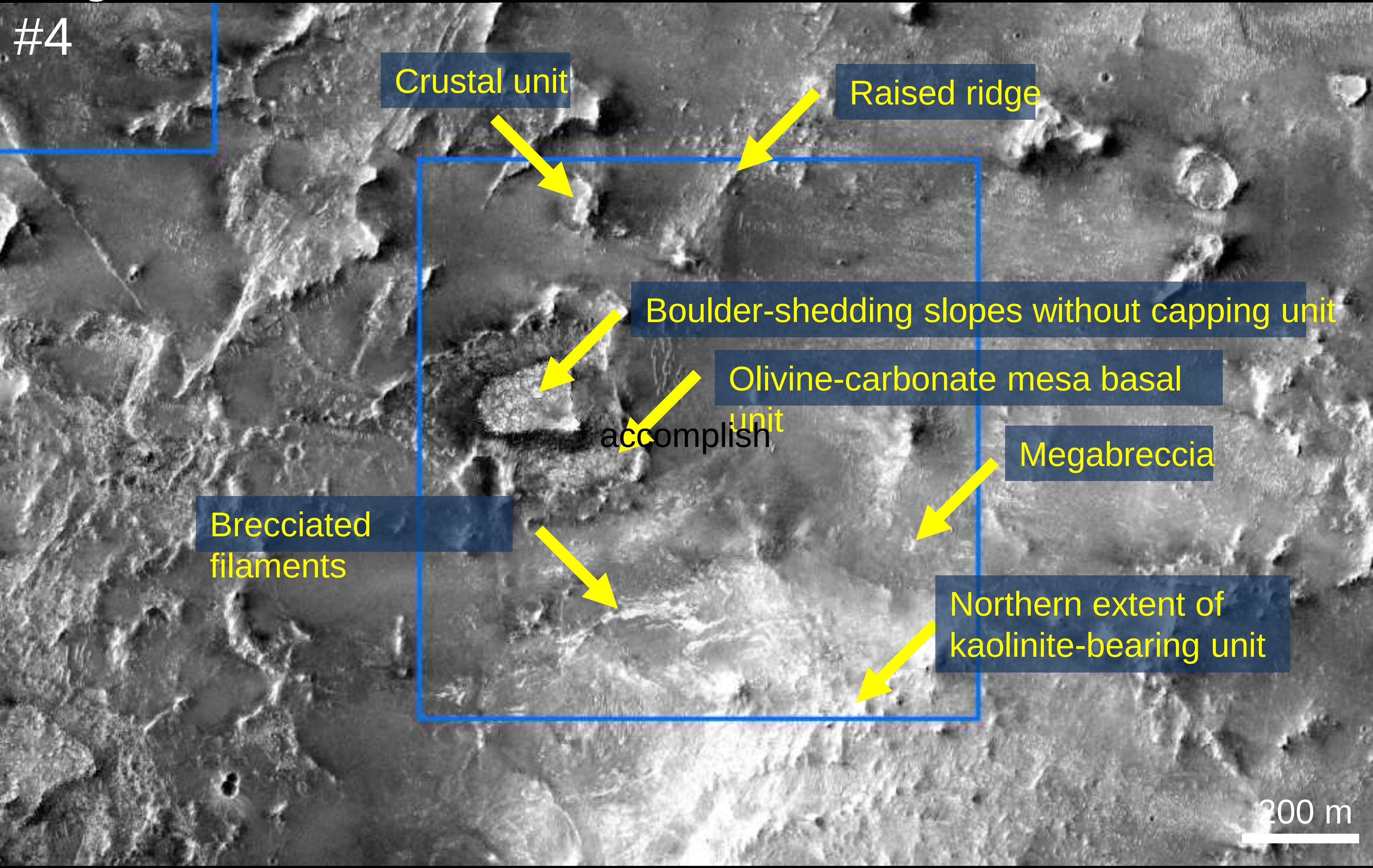
Region of Interest #2



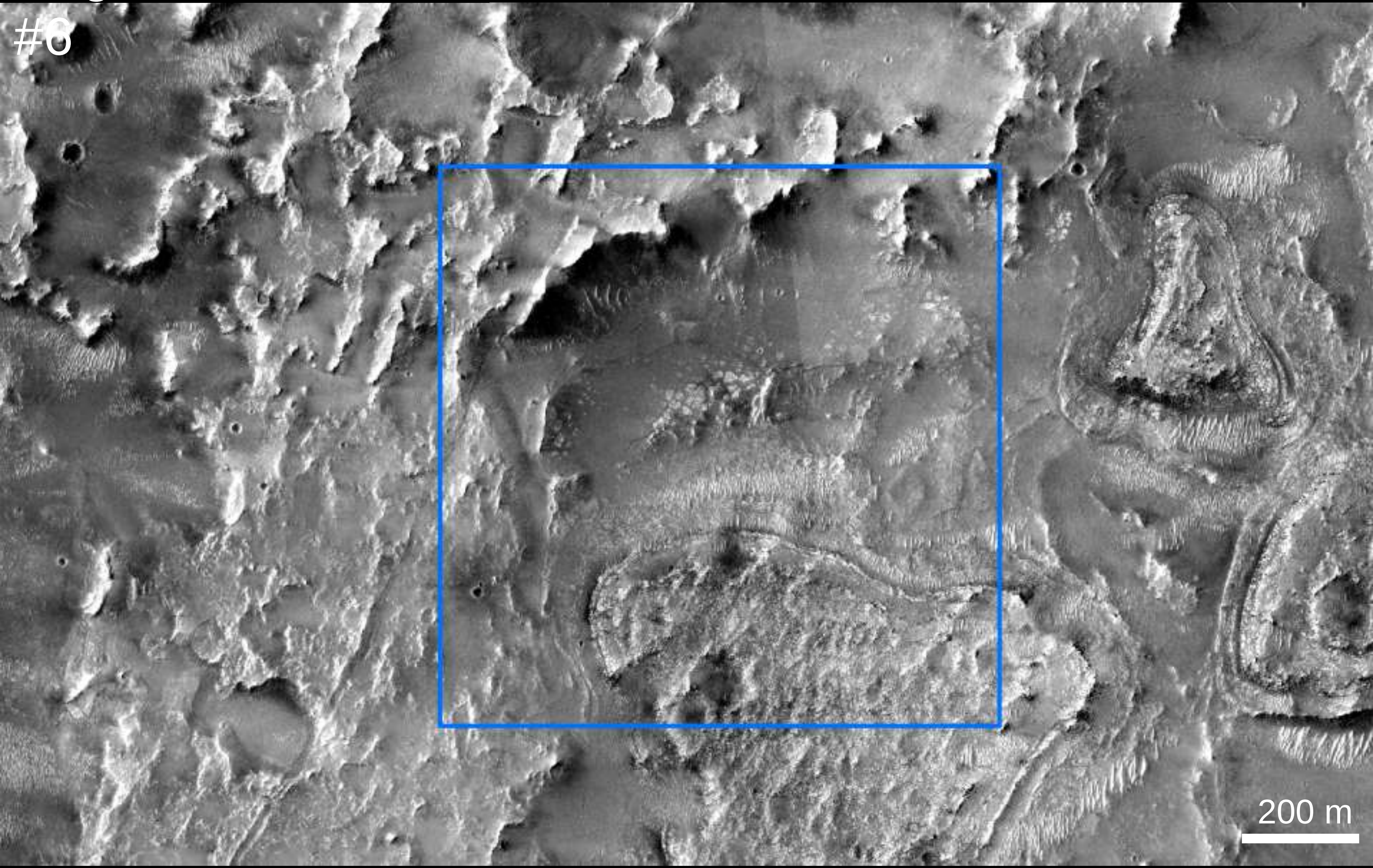
Region of Interest
#4



Region of Interest



Region of Interest



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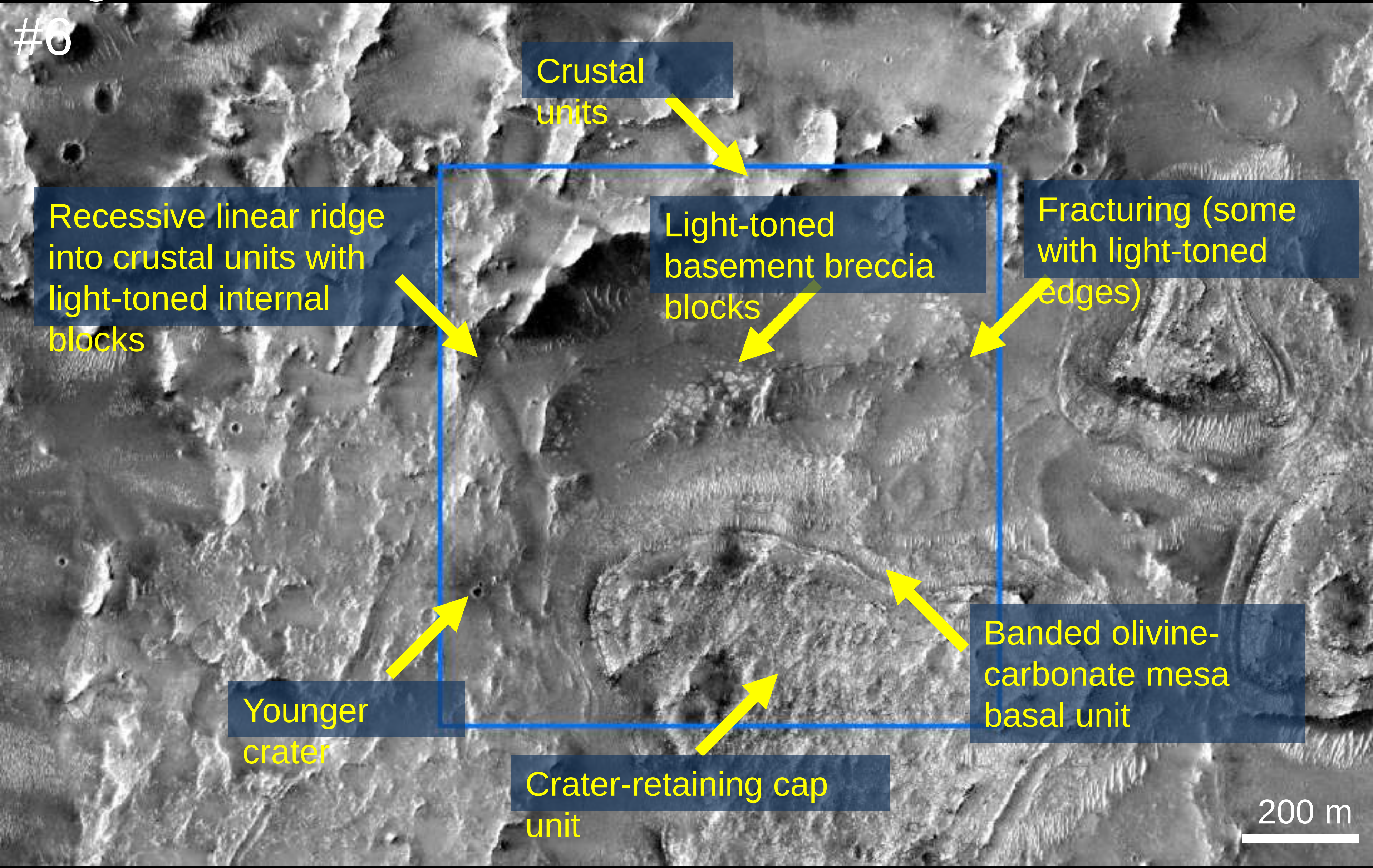
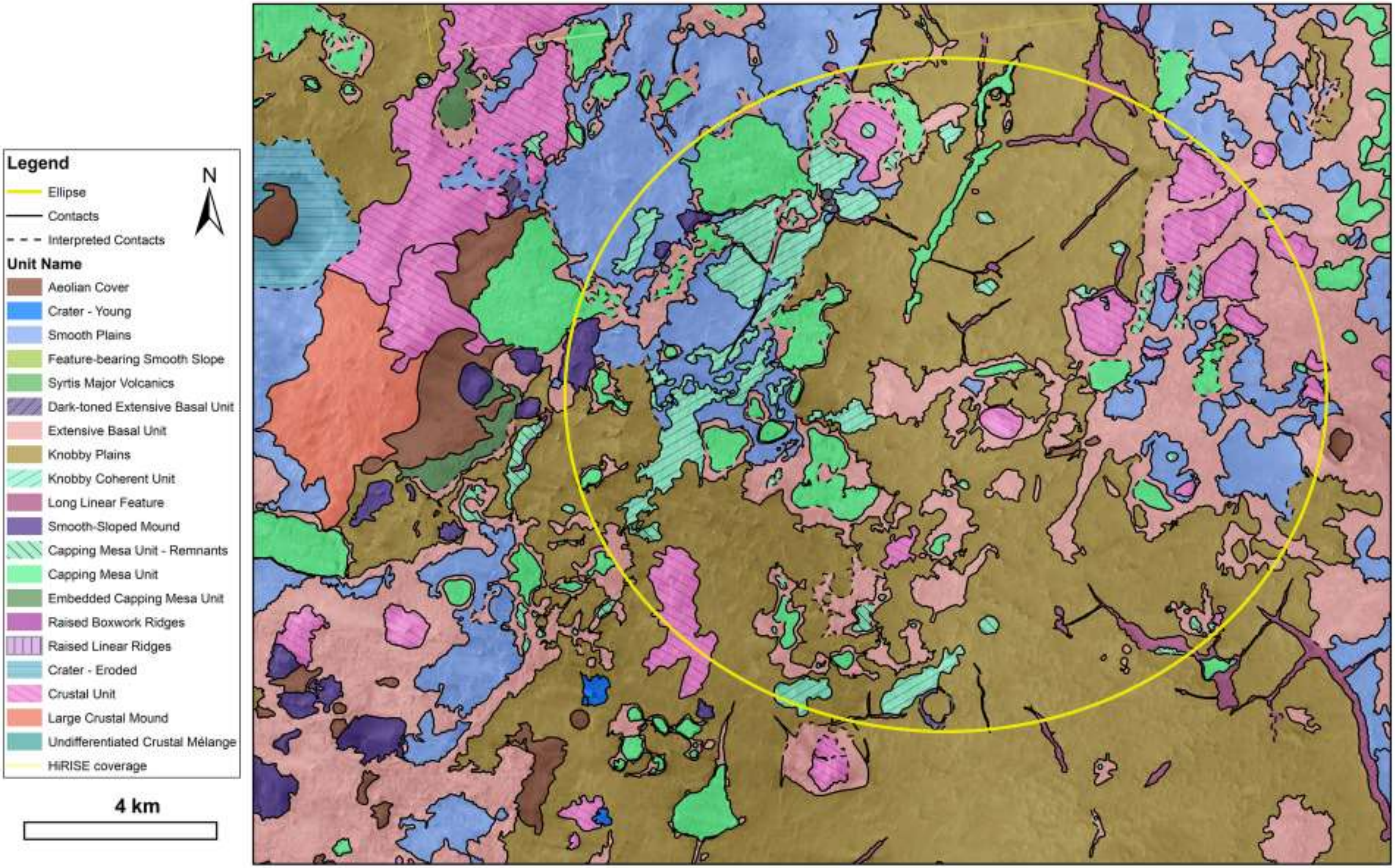
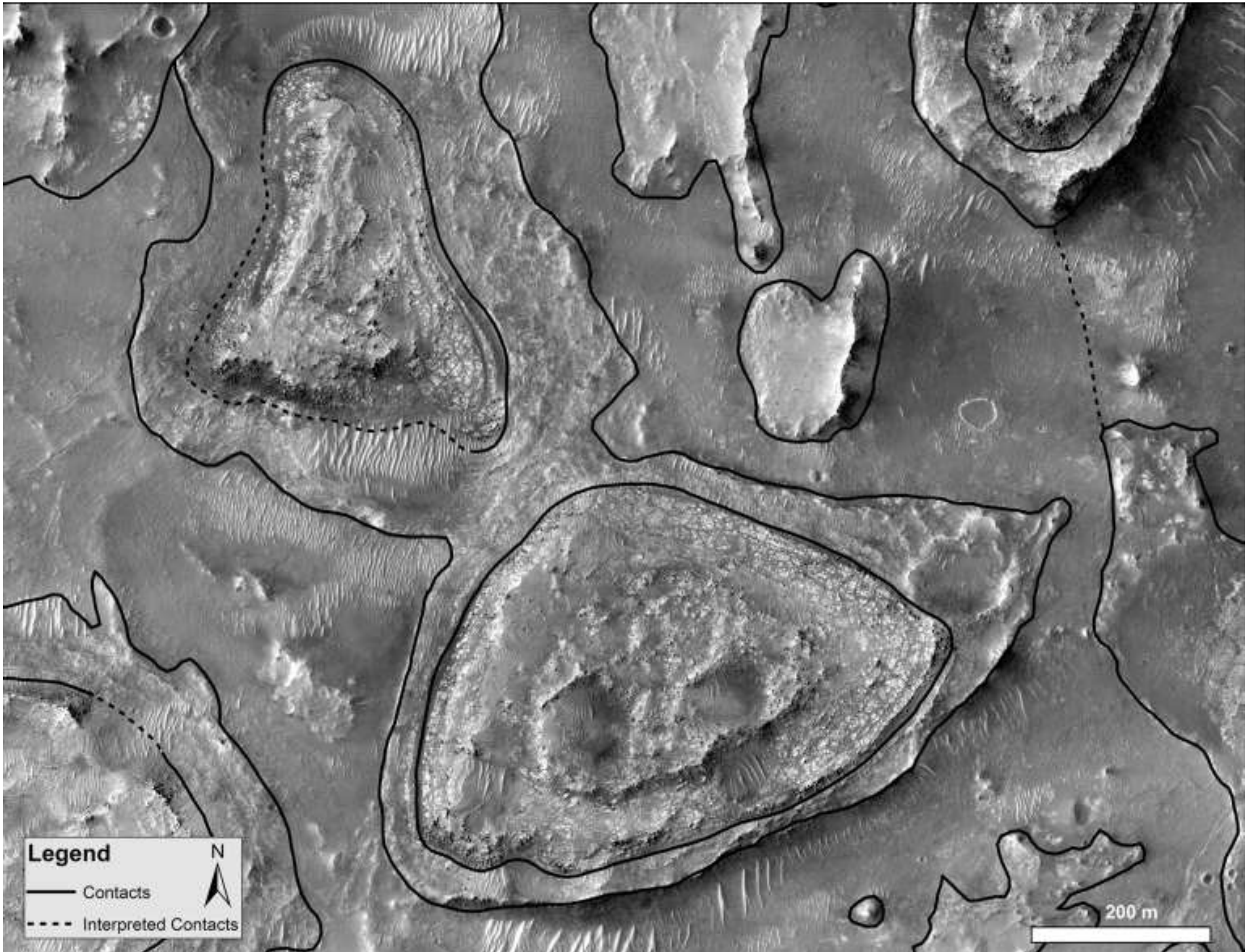


Mapping Northeast Syrtis Major




Legend
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